DTIC FILE COPY

(1)

COMPARATIVE NAVAL ARCHITECTURE OF MODERN FOREIGN SUBMARINES

AD-A202 251

by

John K. Stenard, LT, USN

S.B. Mechanical Engineering, Massachusetts Institute of Technology, May 1980

SUBMITTED TO THE DEPARTMENT OF OCEAN ENGINEERING IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

May 1988

DTIC ELECTE NOV 23 1988 S D

Copyright (c) 1988 John K. Stenard,
The author grants to the Massachusetts Institute of Technology
and to the United States Government and its Agencies
the right to copy this document in whole or in part.

DISTRIBUTION STATEMENT A
Approved for public release;
Distribution Unlimited

Signature of Author John K. Stenard LT, USN
Department of Ocean Engineering
May 27, 1988

Certified by Paul E. Sullivan
Professor Paul E. Sullivan
Thesis Supervisor

Accepted by A. Douglas Carmichael
Professor A. Douglas Carmichael
~~Professor~~ Professor of Power Engineering,
Chairman, Department Committee on Graduate Students

88 11 21 094

COMPARATIVE NAVAL ARCHITECTURE OF MODERN FOREIGN SUBMARINES

by

John K. Stenard, LT, USN

Submitted to the Department of Ocean Engineering on May 27, 1988 in partial fulfillment of the requirements for the degree of Master of Science.

Abstract

A comparative design study of ten conventional and nuclear-powered fast attack submarines is performed. Data sources are limited to those available in the open literature. The analysis is confined to those submarines which are of the greatest interest and for which enough design information is available to conduct an adequate study. The data for each of the selected submarines is then parameterized, analyzed, and compared on the basis of design and military capabilities. The design philosophy and top level requirement of each submarine is then inferred from its naval architecture and military capabilities. It is concluded that automation of systems will allow a reduction of crew size, which then permits a larger battery and greater provision, fuel, and weapons loadouts. This will lead to greater combat effectiveness due to increased range, attack flexibility, speed, and weapons delivery potential.

QUALITY INSPECTED 2

Accesion For
NTIS CRA&I ☒
DTIC TAB ☐
Unannounced ☐
Justification

By
Distribution

Dist
A-1

Thesis Supervisor: Professor Paul E. Sullivan
Title: Associate Professor of Naval Architecture

Dedication

I dedicate this work to the hope that through the maintenance of a strong and effective defense by the United States, the world may avoid the waste and tragedy of armed conflict.

I extend my sincere appreciation and thanks to Professor Paul E. Sullivan, for educating me on submarine design parameters, greatly assisting me in the extensive literature search, and helping me define the focus of this study, and whose patience during the preparation of this document allowed me the freedom to be most effective.

My sincere thanks and admiration go to Harry Jackson, P.E., CAPT USN (Ret.) who, although known as a world-class expert on submarine design, extended to me an open-door policy to his home and personal library, and who provided mature engineering guidance to me on several occasions as I developed the computer models of each of the submarines.

I wish to thank my parents, John D. and Ann E. Stenard, for always being loving and supportive of me, my brothers and sisters, and my family.

My special thanks go to my wife, Amy, for being the love of my life, and for always standing by me, as my partner for life. She also contributed immeasureably to the quality of this document by proofreading it. My special thanks also to our two sons, John G. and James, for being such good little guys.

Table of Contents

Abstract	2
Dedication	4
Table of Contents	5
List of Appendices	7
List of Figures	8
List of Tables	9
Key to the Tables and Figures	11
1. INTRODUCTION	12
2. PURPOSE	14
3. SUMMARY OF SUBMARINES	15
4. DATA GATHERING AND SOURCES OF ERROR	27
4.1 Reference Convention	28
5. METHODOLOGY	29
6. VOLUME ANALYSIS	30
6.1 Volume Within the Pressure Hull	30
6.2 Volume External to Pressure Hull	31
6.3 Discussion	34
6.4 Volume Allocation	36
7. DISPLACEMENT AND WEIGHT ANALYSIS	39
7.1 Displacements	39
7.2 Functional Group Weights	42
8. MILITARY PERFORMANCE	46
8.1 Propulsion and Mobility	46
8.1.1 Required Shaft Horsepower	46
8.1.2 Fuel Endurance Range	52
8.1.3 Battery Endurance Range	54
8.1.4 Indiscretion Rate and Interval	57
8.1.5 Overall Endurance Range	57
8.2 Weapons Systems	60
8.2.1 Weapons Launching Systems	60
8.2.2 Torpedoes	69
8.2.3 Cruise Missiles	69
8.2.4 Mine Laying	70
8.2.5 Other Weapons Systems	70
8.3 Command. Control, Communication, and Information	71
8.3.1 Sonar	71
8.3.2 Periscopes	72
8.3.3 Radar	72
8.3.4 Electronic Surveillance Measures	75

8.3.5 External Communications	75
8.3.6 Automated Controls	76
8.4 Ship Support	76
8.5 Acoustic Countermeasures	77
8.6 Survivability and Damage Control	79
8.7 Escape and Rescue	82
9. COMPARATIVE NAVAL ARCHITECHTURE	84
9.1 Specific Volumes	84
9.1.1 Mobility	84
9.1.2 Weapons Systems	84
9.1.3 Command, Control, Communications, and Information	87
9.1.4 Ship Support	87
9.2 Mobility Weight/Installed Power	87
9.3 Overall Endurance Ranges at Six and Ten Knots	87
9.4 Battery Endurance Range	88
9.5 Indiscretion Rate and Interval	88
9.6 Escape Capability	91
9.7 Weapons Delivery Capabilities and Platform Efficiencies	91
9.7.1 Torpedoes	91
9.7.2 Cruise Missiles	96
9.7.3 Mines	98
9.8 Conclusions	98
10. AREAS FOR FURTHER STUDY	100
10.1 Maneuvering Characteristics	100
10.2 Weight Distribution	100
10.3 Specific Fuel Consumption Increase at Snorkel	100
10.4 Hull Strength Estimation	101
10.5 Weapons and Sensors Capabilities	101
11. REFERENCES	102

List of Appendices

Appendix A: Geometry Calculations for Estimating Compartment Volumes

Appendix B: Numerical Evaluation of Submarine Wetted Surface Area

Appendix C: Calculation of Required Shaft Horspower Deeply Submerged

Appendix D: Calculation of Additional Shaft Horsepoer Required at Snorkel Depths

Appendix E: Endurance Range

Appendix F: Lead-Acid Battery Power and Energy Characteristics

Appendix G: Calculation of Battery Endurance Range

Appendix H: Calculation of Indiscretion Rate and Interval

Appendix I: Estimation of Weight Groups

Appendix J: Anaerobic Diesel Fuel/Air Loadout Calculation

Appendix K: Factors Affecting Crew Endurance

Appendix L: Factors Affecting Vulnerability and Survivability

Appendix M: Estimation of Hotel Electric Load

Appendix N: Diesel Engine Data

Appendix O: Data on Other Modern Submarines

Appendix P: Diesel Engine Specific Fuel Consumption

Appendix Q: Calculation of Provision Ebndurance Range

Appendix R: Calculation of Prismatic Coefficient

List of Figures

7-1 Volumes of Functional Groups.

7-2 Volume Allocation Comparison.

8-1 Weights of Functional Groups.

8-1 Weight Allocation Comparison.

9-1 Shaft Horsepower Required. (Two sheets)

9-2 Ratio of SHP Required at Snorkel Depth to that Required When Deeply Submerged.

9-3 Snorkeling/Fuel Endurance Range.

9-4 Battery Endurance Range. (Two sheets)

9-5 Indiscretion Rate at 80% Depth of Discharge.

9-6 Indiscretion Interval at 80% Depth of Discharge.

9-7 Provision vs. Fuel Endurance Range. (Five sheets)

10-1 Endurance Range at 6 and 10 Kts.

10-2 Battery Endurance Ranges, At 6, 10, 18, and 25 Kts.

10-3 Indiscretion Rates at 6 and 10 Kts.

10-4 Indiscretion Intervals at 6 and 10 Kts.

10-5 Escape Capability Parameter Comparison.

10-6 Weapons Delivery Comparison 1: Torpedoes

10-7 Weapons Delivery Comparison 2: Cruise Missiles

10-8 Weapons Delivery Comparison 3: Mines

F-1 Available Battery Energy as a Function of Speed, 80% Depth of Discharge.

F-2 Battery Total Power Output at Various Speeds, 80% Depth of Discharge.

P-1 Diesel Engine Specific Fuel Consumption Generic Profile.

List of Tables

7-1 Functional group volumes calculated from measurement of reference pictures. (Two sheets)

8-1 Displacements and functional group weights. (Two sheets)

9-1 Propulsion plant and other mobility group parameters. (Two sheets)

9-2 Weapons systems parameters. (Two sheets)

9-3 Command, Control, Communication, and Information Systems

9-4 Ship support systems parameters.

9-5 Countermeasure outfit.

9-6 Compartment measurements germane to damaged survivability.

9-7 Escape and rescue capabilities.

10-1 Comparison of performance and design parameters. (Two sheets)

A-1 Volume calculation tool "SECTOR3.WK1".

B-1 Numerical interpolation and surface integration spreadsheet "SPLINSUB.WK1". (Thirteen sheets)

B-2 Numerical interpolation and surface integration spread- sheet "HERMFAST.WK1". (Thirteen sheets)

C-1 Calculated values of required shaft horsepower (SHP) as a function of speed. (Two sheets)

D-1 The calculated values of required shaft horsepower when operating at snorkel depth. (Two sheets)

E-1 Calculated values of endurance range based upon bunker fuel loadout. (Two sheets)

F-1 Available energy from each submarine battery at several transit speeds. 80% depth of discharge. (Two sheets)

G-1 Calculated values of each submarine's endurance range on batteries alone. 80% depth of discharge. (Two sheets)

H-1 Calculated values of indiscretion rates at various speeds. (Two sheets)

H-2 Calculated values of indiscetion interval as a function of submerged speed. (Two sheets)

N-1 Diesel engine and electric propulsion motor data.

O-1 Data on several other modern submarines, from the lit- erature. (Five sheets)

P-1 Estimated diesel engine specific fuel consumption, as a function of speed. (Two sheets)

Q-1 Provision endurance, in nautical miles, at various speeds.

R-1 Calculation of prismatic coefficient.

Key to the Tables and Figures

Number Submarine

#1 KILO

#2 WALRUS

#3 RUBIS

#4 BARBEL

#5 TYPE 2400

#6 TYPE 1700

#7 TYPE 2000

#8 SAURO

#9 VASTERGOTLAND

#10 MIDGET 100

Chapter 1

INTRODUCTION

The introduction of the submarine added a new dimension to the conduct of naval conflict; that of a potent undetected threat within striking distance. The ability of the submarine to travel from place to place and observe events undetected usually gives to the submarine the ability to attack first (or to decide not to attack) and has always been its greatest asset. The traditional weapon of the submarine has been the torpedo, which because of its underwater attack mode is particularly damaging to surface ships.

Today, the ability of the submarine to remain undetected is still its greatest asset. Technical advances in hydrodynamics, propulsion plant design, and acoustic silencing have made modern submarines more difficult to detect than ever. Similarly, the firepower of the submarine has increased greatly due to technical advances in submarine launched weapons systems.

Many nations include submarines as an important part of their fleet. Several navies consider their submarines to be their capital ships, and employ them for many peacetime uses. Some of the peacetime uses are oceanographic exploration and surveillance.

The primary wartime role of the submarine could be considered to be the same as it always has been, that of interdiction of sea traffic lanes, but the methods of accomplishing this task have been expanded, since most modern submarines are capable of loading mines and encapsulated cruise missiles as well as torpedoes.

The mining capability allows a nation to restrict or deny the use of a port or seaway choke-point to an adversary. This is a very important capability, and is possible for only a submarine in many cases, since a submarine can conduct mining operations under conditions infeasible for aircraft or surface ships. In addition, the mining can be conducted in a covert manner, which is essential in this day of cruise missile shore batteries.

The capability of a submarine to carry cruise missiles gives it the medium-range (50 nautical mile) stand-off attack mode against surface targets. This mode was previously the province of only surface ships and attack aircraft. Long-range strategic nuclear cruise missiles and rocket-propelled homing torpedoes have also been discussed and are in development for attack submarine loadout.

The sophistication of modern torpedoes has increased their range, speed, probability of hit, and overall lethality. While this thesis does not discuss weapons effects, it is generally accepted that a subsurface explosion is much more damaging to a surface ship than an equally-sized explosion in the superstructure. The weapon of choice for attack submarines is still considered to be some variation of the torpedo.

This thesis focuses primarily upon basic mission capabilities such as number and type of weapons carried, maximum speed, maximum mission length, submerged endurance range, and indiscretion rate of diesel-electric submarines. One small nuclear-powered craft is included for comparison. All of the submarines selected for analysis are "attack boats", as opposed to strategic nuclear ballistic missile submarines.

Design data for the craft studied in this thesis is analyzed in a comparative technique, which starts with a gross characteristics comparison. After gross differences are identified, a detailed study of several aspects of the designs is undertaken. Emphasis is placed upon identifying design differences, and on trying to establish the reason for these differences.

Chapter 2

PURPOSE

The purpose of this thesis is twofold:

(1). To determine the capability of each of the selected submarines in terms of primary mission areas, which are generally of a military nature.

(2). To gain a greater understanding of naval architecture in general and submarine design in particular.

Chapter 3

SUMMARY OF SUBMARINES

The literature search having been conducted, the below listed submarines have been selected for inclusion in the detailed analysis portion of this study. They are listed in order of decreasing displacement, followed by the builder's name, country of origin, and year the lead ship was launched.

(1) KILO (Komsomolsk Shipyard, Union of Soviet Socialist Republics, 1980).

(2) WALRUS (Rotterdamsche Droogdok Maatschappij B.V., The Netherlands, 1985)

(3) SSN RUBIS (Cherbourg Naval Dockyard, France, 1979).

(4) BARBEL (Portsmouth Naval Shipyard, United States, 1959).

(5) TYPE 2400 "UPHOLDER" (Vickers Shipbuilding and Engineering Ltd., Great Britain, 1986).

(6) TYPE 1700 (Thyssen Shipyard, Federal German Republic, 1982).

(7) TYPE 2000 (Ingenierkontor-Lubeck, Federal German Republic, 1983).

(8) SAURO (Fincantieri Shipyard, Italy, 1979).

(9) VASTERGOTLAND (Kockums Shipyard, Sweden, 1986).

(10) MIDGET 100 (Sub Sea Oil Services of Micoperi, Italy, 1984).

The BARBEL Class is included because it was the last diesel-electric submarine class to be constructed by the United States. The KILO Class is included because of its interest and widespread use among Communist Bloc and allied nations, and because it represents a state-of-the-art Soviet diesel-electric submarine. The RUBIS, a small nuclear-powered submarine, is included in the study to show the impact of its propulsion plant, compared to other designs.

The following pages summarize the gross attributes of the above selected submarine classes.

KILO
Komsomolsk Shipyard
Union of Soviet Socialist Republics
1980

Submerged Displacement: 3200 Lton
Surface Displacement: 2500 Lton
Standard Displacement: 1900 Lton (Estimate)

Length: 229.6 ft
Surfaced Draft: 23.0 ft
Diameter: 29.5 ft

Complement: 55 Men.

Prime Mover Type: Diesel Engine/Storage Battery
Diesel/Alternator Capacity: 4480 KW
Main Propulsion Motor Power: 4000 HP

Maximum Submerged Speed: 18 Kts (Calculated)
Maximum Surface Speed: 12 Kts (Estimate)
Maximum Snorkel Speed: 10 Kts (Estimate)

Diving Depth: 300 meters (Estimate)

Overall Endurance Range at Six Kts: 5760 Nm
Overall Endurance Range at Ten Kts: 9600 Nm
Maximum Mission Duration: 45 Days

Active Sonar.
Passive Sonar.
Array Sonar.
Navigation Radar.
Electronic Surveillance Gear.

Number of Torpedo Tubes: 8
Number of Reloads Carried: 10

Cruise Missile Capable.
May carry and launch a maximum of 18 SSN-21

Capable of Minelaying.
Maximum Possible Number of Mines Carried: 20

Not Capable of Delivering Swimmers.

WALRUS
Rotterdamsche Droogdok Maatschappij B.V.
The Netherlands
1985

Submerged Displacement: 2800 Lton
Surface Displacement: 2450 Lton
Standard Displacement: 1900 Lton

Length: 223.1 ft
Surfaced Draft: 21.6 ft
Diameter: 27.6 ft

Complement: 50 Men.

Prime Mover Type: Diesel Engine/Storage Battery
Diesel/Alternator Capacity: 5170 KW
Main Propulsion Motor Power: 5360 HP

Maximum Submerged Speed: 20 Kts
Maximum Surface Speed: 12 Kts
Maximum Snorkel Speed: 12 Kts

Diving Depth: In excess of 300 meters.

Overall Endurance Range at Six Kts: 10080 Nm
Overall Endurance Range at Ten Kts: 7178 Nm
Maximum Mission Duration: 70 Days

Active Sonar.
Passive Sonar.
Array Sonar.
Navigation Radar.
Electronic Surveillance Gear.

Number of Torpedo Tubes: 4
Number of Reloads Carried: 20

Cruise Missile Capable.
May carry and launch the SubHarpoon.
Max number Carried: 26

Can carry and emplace 40 mines.

RUBIS
Cherbourg Naval Dockyard
France
1979

Submerged Displacement: 2670 Lton
Surface Displacement: 2385 Lton
Standard Displacement: 2250 Lton (Estimate)

Length: 236.5 ft
Surfaced Draft: 21.0 ft
Diameter: 24.9 ft

Complement: 9 Officers, 57 Enlisted Men

Prime Mover Type: Nuclear Reactor,
Liquid Metal Cooling
Prime Mover Power: 48,000 KW
Main Propulsion Motor Power: 10,000 HP

Maximum Submerged Speed: 25 Kts
Maximum Surface Speed: 20 Kts (Est.)

Diving Depth: In excess of 300 meters.

Overall Endurance Range at Six Kts: 8640 Nm
Overall Endurance Range at Ten Kts: 14400 Nm
Maximum Mission Duration: 60 Days

Active Sonar.
Passive Sonar.
Array Sonar.
Navigation Radar.
Electronic Surveillance Gear.

Number of Torpedo Tubes: 4
Number of Reloads Carried: 10

Cruise Missile Capable.
May carry a maximum of 14 SM-39 cruise missiles

Can carry and place 20 mines.

BARBEL
Portsmouth Naval Shipyard
United States
1959

Submerged Displacement: 2369 Lton
Surface Displacement: 2315 Lton
Standard Displacement: 2146 Lton

Length: 219.1 ft
Surfaced Draft: 28 ft
Diameter: 29 ft

Complement: 8 Officers, 69 Enlisted.

Prime Mover Type: Diesel Engine/Storage Battery
Diesel/Alternator Power: 3580 KW
Main Propulsion Motor Power: 3150 HP

Maximum Submerged Speed: 18 Kts (Calculated)
Maximum Surface Speed: 15 Kts
Maximum Snorkel Speed: 10 Kts

Diving Depth: In excess of 120 meters.

Overall Endurance Range at Six Kts: 8640 Nm
Overall Endurance Range at Ten Kts: 9897 Nm
Maximum Mission Duration: 60 Days

Active Sonar.
Passive Sonar.
Array Sonar.
Navigation Radar.
Electronic Surveillance Gear.

Number of Torpedo Tubes: 6
Number of Reloads Carried: 6

Cruise Missile Capable.
May carry and launch the 12 Sub-Harpoon.

Can carry and emplace 12 mines.

Unknown if swimmer capable.

TYPE 2400 "UPHOLDER"
Vickers Shipbuilding & Engineering Ltd.
United Kingdom
1986

Submerged Displacement: 2400 Lton
Surface Displacement: 2188 Lton
Standard Displacement: 1850 Lton

Length: 230.6 ft
Surfaced Draft: 17.7ft
Diameter: 25 ft

Complement: 7 Officers,
13 CPO, 24 Enlisted. (44 Total)

Prime Mover Type: Diesel Engine/Storage Battery
Prime Mover Maximum Power: 3620 HP
Main Propulsion Motor Power: 5360 HP

Maximum Submerged Speed: 20 Kts
Maximum Surface Speed: 12 Kts
Maximum Snorkel Speed: 10 Kts

Diving Depth: In excess of 200 meters.

Overall Endurance Range at Six Kts: 7056 Nm
Overall Endurance Range at Ten Kts: 5221 Nm
Maximum Mission Duration: 49 Days

Active Sonar.
Passive Sonar.
Array Sonar.
Navigation Radar.
Electronic Surveillance Gear.

Number of Torpedo Tubes: 6
Number of Reloads Carried: 12

Cruise Missile Capable.
May carry and launch 12 Sub-Harpoon missiles.

Can carry and emplace 24 mines.

Equipped with airlock for five combat swimmers.

Type 1700
Thyssen Shipyard
Federal German Republic
1984

Submerged Displacement: 2350 Lton
Surface Displacement: 2140 Lton
Standard Displacement: 1760 Lton

Length: 216.5 ft
Surfaced Draft: 21.3 ft
Diameter: 23.9 ft

Complement: 30-35 Men.

Prime Mover Type: Diesel Engine/Storage Battery
Diesel Generator Maximum Power: 4400 KW
Main Propulsion Motor Power: 8844 HP

Maximum Submerged Speed: 25 Kts
Maximum Surface Speed: 15 Kts
Maximum Snorkel Speed: 15 Kts

Diving Depth: In excess of 300 meters.

Overall Endurance Range at Six Kts: 10080 Nm
Overall Endurance Range at Ten Kts: 10736 Nm
Maximum Mission Duration: 70 days

Active Sonar.
Passive Sonar.
Array Sonar.
Navigation Radar.
Electronic Surveillance Gear.

Number of Torpedo Tubes: 6
Number of Reloads Carried: 16

Not Cruise Missile Capable.

Can carry and emplace 32 mines.

Not Capable of Delivering Swimmers.

TYPE 2000
Ingenieurkontor-Lubeck
Federal German Republic
1983

Submerged Displacement: 3106 Lton
Surface Displacement: 2820 Lton
Standard Displacement: 2200 Lton

Length: 210.6 ft
Surfaced Draft: 21 ft
Diameter: 24.4 ft

Complement: 33 Men.

Prime Mover Type: Diesel Engine/Storage Battery
Diesel Generator Maximum Power: 3600 KW
Main Propulsion Motor Power: 7500 HP

Maximum Submerged Speed: 25 Kts
Maximum Surface Speed: 13 Kts
Maximum Snorkel Speed: 15 Kts

Diving Depth:

Overall Endurance Range at Six Kts: 12651 Nm
Overall Endurance Range at Ten Kts: 9293 Nm
Maximum Mission Duration: Days

Number of Torpedo Tubes: 8
Number of Reloads Carried: 18

Not Cruise Missile Capable.

Can carry and emplace 24 mines.

Not Capable of Delivering Swimmers.

SAURO
Fincantieri Shipyard
Italy
1979

Submerged Displacement: 1660 Lton
Surface Displacement: 1480 Lton
Standard Displacement: 1280 Lton

Length: 191 ft
Surfaced Draft: 17 ft
Diameter: 22.4 ft

Complement: 35 Men.

Prime Mover Type: Diesel Engine/Storage Battery
Diesel Generator Maximum Power: 2160 KW
Main Propulsion Motor Power: 3216 HP Continuous
4200 HP (Burst)

Maximum Submerged Speed: 19.3 Kts
Maximum Surface Speed: 11 Kts
Maximum Snorkel Speed: 11 Kts

Diving Depth: In excess of 300 meters.

Overall Endurance Range at Six Kts: 6480 Nm
Overall Endurance Range at Ten Kts: 6891 Nm
Maximum Mission Duration: 45 Days

Active Sonar.
Passive Sonar.
Navigation Radar.
Electronic Surveillance Gear.
VLF Radio Receiver.

Number of Torpedo Tubes: 6
Number of Reloads Carried: 6

Not Cruise Missile Capable.

Can carry and emplace 12 mines.

Not Capable of Delivering Swimmers.

VASTERGOTLAND CLASS
Kockums Shipyard
Sweden
1986

Submerged Displacement:	1150 Lton
Surface Displacement:	1070 Lton
Standard Displacement:	990 Lton

Length:	159.1 ft
Surfaced Draft:	17 ft
Diameter:	20.3 ft

Complement: 21 Men.

Prime Mover Type: Diesel Engine/Storage Battery
Diesel Generator Maximum Power: 2160 KW
Prime Mover Maximum Power: 2680 HP
Main Propulsion Motor Power: 2537 HP

Maximum Submerged Speed: 20 Kts
Maximum Surface Speed: 11 Kts
Maximum Snorkel Speed: 10 Kts (Estimate)

Diving Depth: In excess of 300 meters.

Overall Endurance Range at Six Kts: 3231 Nm
Overall Endurance Range at Ten Kts: 1956 Nm
Maximum Mission Duration: 30 Days

Passive Sonar.
Electronic Surveillance Gear.

Number of Torpedo Tubes:	6 Heavyweight tubes
	3 Lightweight tubes
Number of Reloads Carried:	6 Heavyweight

Not cruise missile capable.

Can carry and emplace 12 mines.
May also carry mines in external belt.

Not Capable of Delivering Swimmers.

MIDGET 100 "LWT 27-4"
Sub Sea Oil Services of Micoperi
Italy
1984

Submerged Displacement: 136 Lton
Surface Displacement: 120 Lton (Estimate)
Standard Displacement: 100 Lton

Length: 88.9 ft (27.1 meters)
Diameter: 10.3 ft

Complement: 12 (+ 4 combat swimmers)

Prime Mover Type: Closed-Cycle Diesel
Small battery installed for stealth.
Main Propulsion Motor Power: 420 HP
Diesel/Generator Total Power: 120 HP

Maximum Sustained Submerged Speed: 16 Kts
Does Not Need to Snorkel.

Diving Depth: In excess of 200 meters.

Overall Endurance Range at Six Kts: 1345 Nm
Overall Endurance Range at Ten Kts: 819 Nm
Maximum Mission Duration: 14 Days

Active/Passive Sonar.
Array Sonar.
Navigation Radar.

Number of Torpedo Tubes: 4 (Lightweight)

Number of Reloads Carried: None (Muzzle Loaded)

Not Cruise Missile Capable.

Twin 7.62mm Deck guns and Single 20mm Deck Gun.

Capable of Minelaying.
Maximum Possible Number of Mines Carried: 4
Variant carries two mine delivery vehicles with
10 x 600Kg mines.

Chapter 4

DATA GATHERING AND SOURCES OF ERROR

There were two methods of data acquisition for this study. The first type was a search of the open literature for articles, advertisements, and manufacturer's brochures of interest. The second data source was that gained by calculation or estimation of values directly or indirectly from the data which could be gleaned from the open literature. Sensitive, proprietary, or classified information, or information gained through such channels, must be excluded from the thesis. Therefore, some of the data in this study is "second-generation" data, calculated or estimated from available published data. This introduces the possibility of error.

In the literature search it was found that some performance figures, such as maximum speed and number of torpedo tubes, were almost always available, usually in Jane's Fighting Ships, (17). Beyond these data elements, the sources were incomplete or, in some cases, contradictory of one another. One reason for some of the contradiction in the literature is probably due to the inevitable unintentional misquote of some corporate or government spokesperson. Literature sources are usually quite close to one another, so that the error introduced was usually not of great significance. For example, a submarine designed to accomodate sixty-two men could doubtlessly sustain a crew of sixty-seven (albeit for a shorter mission duration). One other possible source of literature data discrepancy is that the authors of the articles may not all have the same initial data with which to conduct their analyses. Articles in the literature, as opposed to manufacturer's brochures, are authored by a certain group of naval architects and naval ship analysts, each of which doubtlessly has his own set of empirical relations, correlation coefficients, and rules of thumb with which to conduct his analyses. Even if all of these naval architects were given the same initial data on a given submarine, there is bound to be a certain range of calculated and estimated secondary data values resulting from each of them. Where conflicting values of data exist in the literature, a notation is made, and the author's judgement is used to select the preferred value.

As a result of the problems with the data mentioned above, the accuracy of much of this thesis is probably not grater than ten-percent. This error comes from some things as simple as being unable to measure submarine dimensions with extreme accuracy from an isometric and only partially-exposed cutaway view in a magazine, to the fact that errors will compound when used in calculations.

Care has been taken to limit discussion to obvious design features and differences between ships. The magnitude of the error is, therefore, deemed acceptable for the purpose of this analysis.

4.1 Reference Convention

In the data tables and figures included in this study, the sources of the information are referenced in the following manner:

- Information from the literature is denoted by a number, in parentheses, which corresponds to the reference from which it was taken.
- Values calculated in the course of this study are unreferenced.
- Values or conditions which are estimated by the author, in the author's best judgement, are referenced by an "(e)" next to the entry.
- Values or conditions which are inapplicable to a calculation are designated by "N/A".

Chapter 5

METHODOLOGY

The method by which this thesis was carried out is straightforward, and consists of the following:

(1). Acquisition of available data from open-literature sources.

(2). Calculation or estimation of neccessary data which is not readily available or which could not be found.

(3). Parameterization of each of the selected submarines according to reasonable mathematical indices of description.

(4). Comparison of each of the submarines according to its indices of description.

Finally, an attempt is made to "reverse engineer" the design process of each submarine in order to determine the nature of the top-level requirement.

Chapter 6

VOLUME ANALYSIS

6.1 Volume Within the Pressure Hull

The pressure hull volume distribution is of prime importance in the design of a submarine. The pressure hull volume is determined partly by the size of the payload, but it must also contain and protect the propulsion plant, electronics, weapons, and crew. The tradeoff in volume allocation between each of these areas determines, to an extent, the performance capabilities of the submarine. The overall volume of the pressure hull, and the allocation of that volume, give considerable insight into the design philosophy of each submarine.

The pressure hull of most submarines is composed of sections of cylinders, cones, and spheres. The pressure hull of the MIDGET 100 is one exception, since its pressure hull has the same teardrop shape as its external envelope, rather than cylinders or cones. The pressure hull total volume is readily calculated from the formulas of Appendix A, provided a detailed reference picture of the vessel exists. The reference pictures of the submarines in this study were of detail sufficient to allow calculation of pressure hull volume to within five percent. Reference pictures were not available for KILO and TYPE 2000.

More difficult is the calculation of the volumes of the individual functional areas within the pressure hull. The assignment of pressure hull volumes to each functional area, for the purpose of this study, is defined below. Where two or more functional areas share the same space, a judgement is made of the volume occupied by each function.

(1). Mobility. Includes the spaces housing all propulsion machinery, non-distributed electric plant equipment, bow thrusters, steering gear, batteries, and internal fuel tanks. Also includes trim and auxiliary ballast tanks, and HP air flasks.

(2). Weapons. Includes the volume of the torpedo tubes, handling gear, ejection and launching equipment within the pressure hull, and the volume of the torpedo room, excluding any volume used for berthing.

(3). Command, Control, Communication, and Information, (C3I). Includes radio, sonar, radar, electronic warfare, periscopes, computers, navigation center, and control rooms. Also includes (an arbitrary) forty percent of the air-conditioning plant.

(4). Ship Support. Includes berthing, messing, galley, sanitary, and passageway space. Also includes all auxiliary machinery except that alloted to C3I.

The calculated volumes of each functional group within the pressure hull are shown in Table 7-1.

6.2 Volume External to Pressure Hull

The ballast tank volume is calculated from the difference in the values of the submerged and surfaced displacements, which in general can be found in the literature.

The free flood volume is assumed to be five-percent of the submerged volume. The reference pictures of each submarine tend to confirm that the free flood volume is concentrated primarily in the fairwater, around the bow sonar array and torpedo tubes, and at the stern in the vicinity of the shaft.

The envelope volume of each submarine is estimated by summing the submerged volume and the free flood volume.

The remaining volume external to the pressure hull is found by subtracting the ballast tank volume and the pressure hull volume from the envelope volume. The other volume

VOLUMES (in cubic feet)	KILO	WALRUS	RUBIS	BARBEL	TYPE 2400
	SUBMARINE NAME				
WITHIN PRESSURE HULL					
MOBILITY VOL	33000	33527	48042	25630	37044
WEAPONS VOL	10000	9281	10176	7290	6724
C3I SYSTEMS VOL	11000	5900	5890	6701	9127
SHIP SUPPORT VOL	14000	27752	15990	14562	11428
TOTAL:	68000	76460	80098	54183	64323
EXTERNAL TO PRESSURE HULL					
BALLAST TANK VOL	24500	12250	9975	11340	8400
OTHER SUBMRGD VOL	19500	9290	3377	26842	11277
TOTL SUBMRGD VOL	112000	98000	93450	92365	84000
ASSUMED FREEFLOOD	5600	4900	4672.	4618.	4200
TOTAL ENVLPE VOL	117600	102900	98122	96983	88200
REFERENCE DRAWING FOR MEASUREMENTS:	(e)	(18)	(10)	(35)	(13)

Table 7-1: Functional group volumes calculated from measurement of reference pictures. (Sheet one of two).

VOLUMES (in cubic feet)	TYPE 1700	TYPE 2000	SAURO	VASTER-GOTLAND	MIDGET 100
	SUBMARINE NAME				
WITHIN PRESSURE HULL					
MOBILITY VOL	50021	44000	23775	17488	957
WEAPONS VOL	5676	6000	8589	7092	405
C3I SYSTEMS VOL	4806	5300	7290	4803	743
SHIP SUPPORT VOL	10043	10000	9817	7564	1265
TOTAL:	70546	65300	49471	36947	3370
EXTERNAL TO PRESSURE HULL					
BALLAST TANK VOL	7350	9310	6300	2450	420
OTHER SUBMRGD VOL	4354	6940	2329	503	970
TOTAL SUBMRGD VOL	82250	81550	58100	39900	4760
ASSUMED FREEFLOOD	4112.	4078	2905	1995	238
TOTAL ENVLPE VOL	86362	85628	61005	41895	4998
REFERENCE DRAWING FOR MEASUREMENTS:	(2)	(e)	(12)	(36)	(29)

Table 7-1: Functional group volumes calculated from measurement of reference pictures. (Sheet two of two).

may be made up of structure, fuel tanks, high-pressure air flasks, conformal or trailed sonar arrays, periscopes and masts, snorkel, fittings, and special-purpose equipment.

Table 7-1 shows the calculated values of each submarine's main ballast tank and free flood volume, other submerged volume, and the envelope volume.

6.3 Discussion

Figure 7-1 graphically depicts the actual measured and calculated volumes of each of the functional groups, plus main ballast tank volume and other volume external to the pressure hull, for each of the submarines. The volumes for KILO and TYPE 2000 are estimated, since reference pictures were not available.

The first item of interest in Figure 7-1 is the variance in scale between the ten submarines in this study. The largest boat, KILO, is over twenty-three times the size of the MIDGET 100, with the other submarines falling between those extremes. Since Figure 7-1 displays each of the actual functional area volumes, it is possible to compare the sizes of each submarines' weapons area, or electronics/command suites by inspection.

The C3I functional group volume is largest in the KILO of all the submarines. Though the installed electronic equipment aboard KILO is not thought to be any greater than that installed in the other submarines, Soviet electronics are probably more voluminous than similar Western electronics because of the extensive use of vacuum tubes rather than solid-state technology. The C3I volumes for the WALRUS, RUBIS, BARBEL, TYPE 1700, TYPE 2000, and VASTERGOTLAND are nearly the same, even though the vessels vary in submerged displacement by a factor of two from the smallest to the largest. This demonstrates that the volume required to enclose sensor electronics and a command center aboard an oceangoing submarine is not a strong function of the vessel displacement.

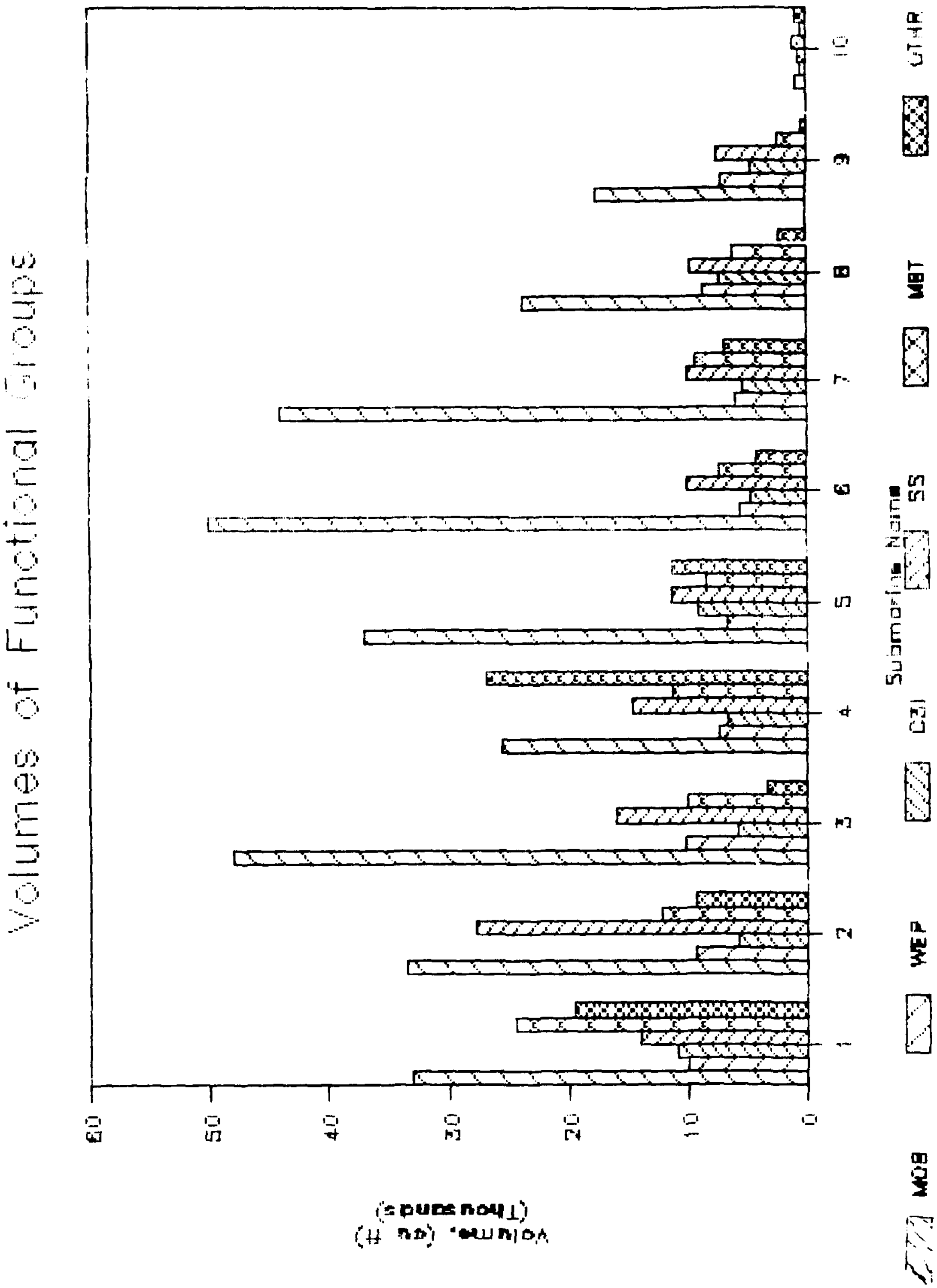


Figure 7-1: Volumes of submarine functional groups.

Figure 7-1 shows the actual volumes of each of the functional groups, plus main ballast and other external volume, for each submarine. Some values are immediatly noticed in Figure 7-1, such as the large mobility volumes for the RUBIS, TYPE 1700, and TYPE 2000, each of which has a large propulsion plant. In fact they have the three largest installed shaft horsepower plants of the submarines studied, and together have more horsepower than the remaining seven combined. The TYPE 1700 and the TYPE 2000 have larger batteries than the others, and the RUBIS has a nuclear reactor contributing to the volume. Also noticable are the small mobility volumes for the VASTERGOTLAND and the MIDGET 100, each of which have less-powerful propulsion plants, and smaller batteries than the others.

The BARBEL and KILO each have large non-ballast volumes external to the pressure hull. The KILO has this volume because of its double-hull, the BARBEL because of the placement of large banana-shaped high-pressure air tanks between the pressure hull and the hydrodynamic envelope.

The ship support volume of each submarine would be considered a function of the complement, but each designer/builder has a different opinion of the habitability standards required by a submarine crew. Appendix K discusses some factors affecting crew endurance, not the least of which is volume-per-man within the pressure hull. The large differences in ship support volume among the submarines does not correlate to the variances in their complements. Chapter 10 discusses this in greater detail.

6.4 Volume Allocation

The allocation of volume in a submarine can indicate the functional groups which were most important to its designer. Figure 7-2 shows the volume distribution of each submarine. Note the high fraction of the volume dedicated to mobility in RUBIS, TYPE 1700, and TYPE 2000.

KILO and BARBEL have large non-ballast volumes external to the pressure hull, because of their double-hull conmstruction. This volume is proportionately large in MIDGET 100 also, but it is due to the disproportionately large fairwater which cannot be made smaller or it would be unusable.

WALRUS and MIDGET 100 have very high ship support fractions. This was probably planned in the case of WALRUS, because of its long mission duration. For MIDGET 100, it is unavoidable due to the scale effect of having the diameter of the vessel comparable to the human body height.

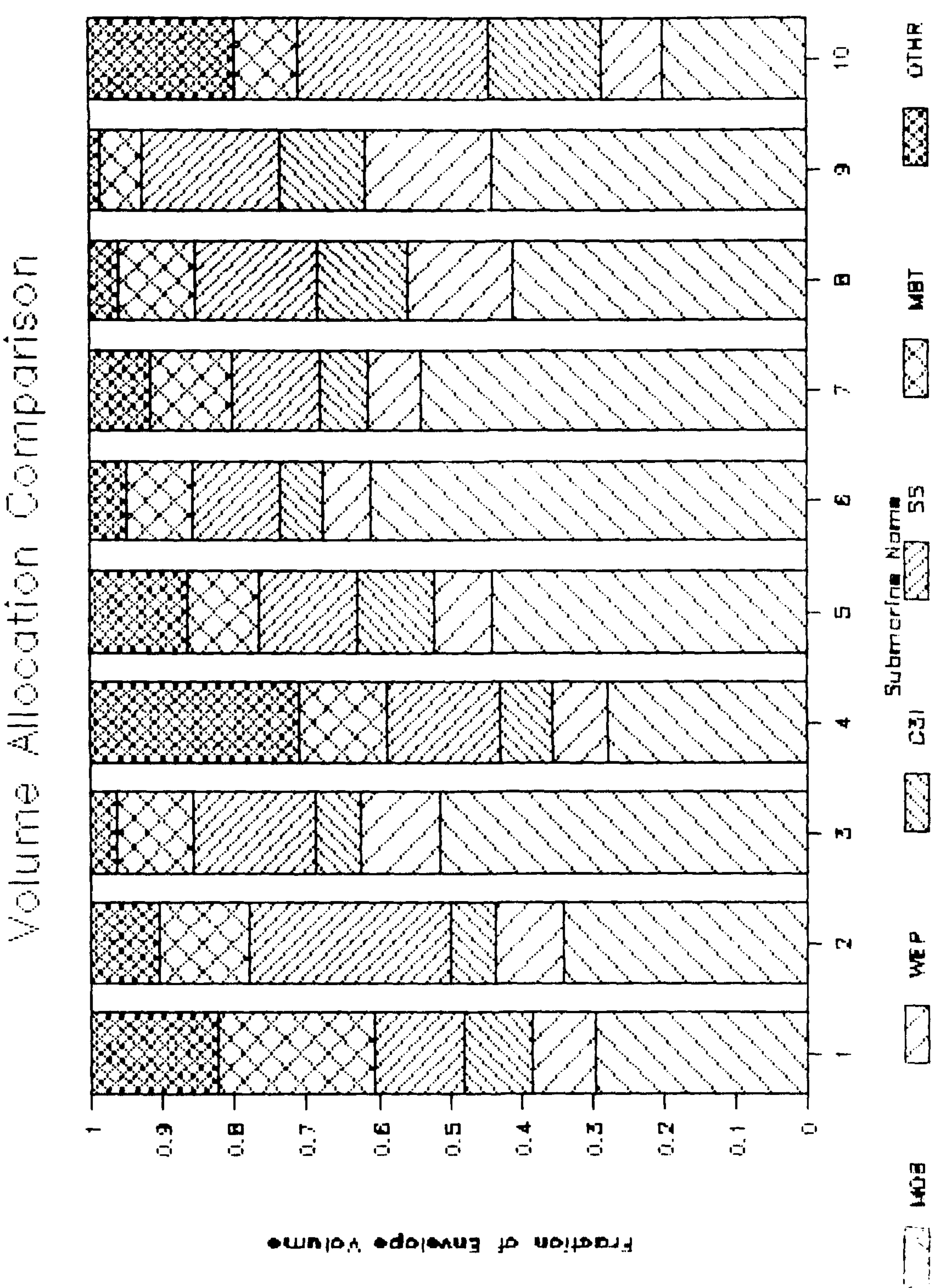


Figure 7-2: Submarine volume allocation comparison.

Chapter 7

DISPLACEMENT AND WEIGHT ANALYSIS

7.1 Displacements

Each submarine may be described by three displacements:

1. Standard displacement is the displacement of the submarine on the surface when unloaded with fuel, ammunition, provisions, and crew.

2. Surface displacement is the displacement of the submarine on the surface when loaded with fuel, ammunition, provisions, and crew. It is equal to the standard displacement plus variable loads.

3. Submerged displacement is the displacement of the submarine when loaded, operating submerged. It is equal to the surface displacement plus main ballast tanks.

The literature has many of the values of these displacements, but in many cases the values differ slightly from one reference to the next. The literature usually provides no more than two of the three displacements, but knowledge of two can yield a reasonable estmate of the third. The variable loads and the ballast tank weight can be calculated from these known displacements, or if known, can be used to calculate the displacements.

Table 8-1 lists the displacement values for each of the submarines. Also shown are the weights of the variable loads and main ballast tanks.

It should be noted that diesel electric submarines must have large-capacity auxiliary ballast tanks to compensate for the lost weight of the bunker fuel. Alternatively, and preferably, is the installation of a fuel compensating system, and using the fuel tanks as

SUBMARINE NAME										
DISPLACEMENTS (Ltons)	KILO	REF	WALRUS	REF	RUBIS	REF	BARBEL	REF	TYPE 2400	REF
STANDARD DISPLCMNT	1900	(e)	1900	(21)	2250	(e)	2146	(34)	1850	(17)
VARIABLE LOADS	600		550		135		169		310	
SURFACE DISPLCMNT	2500	(17)	2450	(21)	2385	(10)	2315	(34)	2160	(32)
MN BALLAST TNKS	700		350		285		324		240	
SUBMERGD DISPLCMNT	3200	(17)	2800	(21)	2670	(17)	2639	(34)	2400	(32)

FUNCTIONAL GROUP WEIGHTS	KILO 1700	WALRUS REF	RUBIS 2000	BARBEL		TYPE 2400
VARIABLE LOADS	600	550	135	169	(34)	310
BALLAST TANK	700	350	285	324	(34)	240

Unless otherwise referenced, the following weights are from Appendix I.

MOBILITY MACHNRY	700	792	1073	575	(34)	868
WEAPONS SYSTEMS	78	48	53	64	(34)	60
C3I SYSTEMS	67	50	53	56	(34)	84
SHIP SUPPORT	101	98	127	117	(34)	101
STRUCTURAL WEIGHT	825	787	814	820	(34)	618
FIXED BALLAST (5%)	128	125	129	514	(34)	119
SUBMERGD DISPLCMNT	3200	2800	2670	2639		2400

Table 8-1: Displacements and functional group weights. (Sheet one of two).

DISPLACEMENTS (Ltons)	TYPE 1700	REF	TYPE 2000	REF	SAURO	REF	VASTER-GOTL'D	REF	MIDGET 100	REF
STANDARD DISPLCMNT	1760	(6)	1800	(6)	1280	(12)	990	(17)	100	(1)
VARIABLE LOADS	380		264		200		80		24	
SURFACE DISPLCMNT	2140	(5)	2064	(e)	1480	(12)	1070	(36)	124	(e)
MN BALLAST TNKS	210		266		180		70		12	
SUBMERGD DISPLCMNT	2350	(e)	2330	(6)	1660	(12)	1140	(6)	136	(1)

WEIGHTS (Ltons)	TYPE 1700	TYPE 2000	SAURO	VASTER-GOTL'D	MIDGET 100
VARIABLE LOADS	380	264	200	80	24
BALLAST TANK	210	266	180	70	12
Unless otherwise referenced, the following weights are from Appendix I.					
MOBILITY MACHNRY	988	922	533	420	34
WEAPONS SYSTEMS	42	59	71	78	16
C3I SYSTEMS	32	40	61	41	6
SHIP SUPPORT	67	76	70	49	8
STRUCTURAL WEIGHT	544	611	470	346	30
FIXED BALLAST	86	93	75	55	6
SUBMERGD DISPLCMNT	2350	2330	1660	1140	136

Table 8-1: Displacements and functional group weights. (Sheet two of two).

auxiliary ballast tanks. This necessitates the installation of a reliable and effective fuel oil filter and coalescer system as well. The literature was inconclusive about the presence of fuel-compensating systems, except for the TYPE 2400, which does, Reference (32).

The ballast tank weight is a big selling point and is also a matter of contention among submarine builders and designers. In the event of hull damage severe enough to cause flooding of the submarine, the bouyancy lost to the flooding water may be recovered, at least temporarily, by blowing down the main ballast tanks, hence their alias as "reserve bouyancy". Creating volume on a submarine is expensive, and even the extra ballast tank volume to accomodate a little extra reserve bouyancy will cost, in terms of speed, range, payload, crew habitabilly, electronics, or construction cost. At the same time, it is acknowledged that each manufacturer wishes to present his product in the best light possible, and it is desirable to have large main ballast tanks, hence the source of the tradeoff.

7.2 Functional Group Weights

The weights of specific machinery and other equipment aboard the submarines could not be found in the literature. To estimate the functional group weights, empirical formulas were developed which related data parameters which are found in the literature to the elusive weight groups. Reference (16) was crucial in this regard. The details of this process are described in Appendix I. The result of the Appendix I calculations for functional group weights are listed in Table 8-1.

A rigorous analysis of the functional group weights given in Table 8-1 would be tongue-in-cheek at best, since nearly all the weights are calculated from the same empirical formulas. Instead, a qualitative approach will be taken in relating the weight groups of each submarine to the other submarines, to attempt to understand how the overall performance of each submarine is affected by the weights of its functional groups.

Using this approach, and with the aid of Figures 8-1 and 8-2, one may see that the boats with the higher top speeds and longer endurance ranges, such as RUBIS, TYPE 1700, and TYPE 2000, have the higher weights in the mobility functional area. Those with lower top speeds, such as BARBEL, KILO, and MIDGET 100 have proportionately smaller mobility weights.

The weights of the ship support, C3I, and weapons functional groups are small compared with the displacement of the corresponding submarine. This reflects the nature of the materials from which these groups are constructed. It also reflects the weight density of the spaces associated with those functional groups. It is reasonable to expect that diesel engines, alternators, and lead-acid batteries make up a much larger proportion of the displacement of the submarine than habitability or electronics spaces.

The vessels rated at a shallower immersion depth, TYPE 2400 and MIDGET 100, have a smaller proportion of their displacement attributed to structural weight. An exception is BARBEL, rated at 120 meters immersion, whose structural weight is proportionatly as great as submarines rated at 300 meters immersion. One reason for its higher structural weight is that it, and KILO as well, is a double-hull design. One could conclude that the empirical formulas of Appendix I are inaccurate by a factor of three, that the formulas may be accurate but BARBEL is fabricated of a weaker material than the more modern submarines, or that the formulas are accurate, but BARBEL is underrated at only 120 meters immersion.

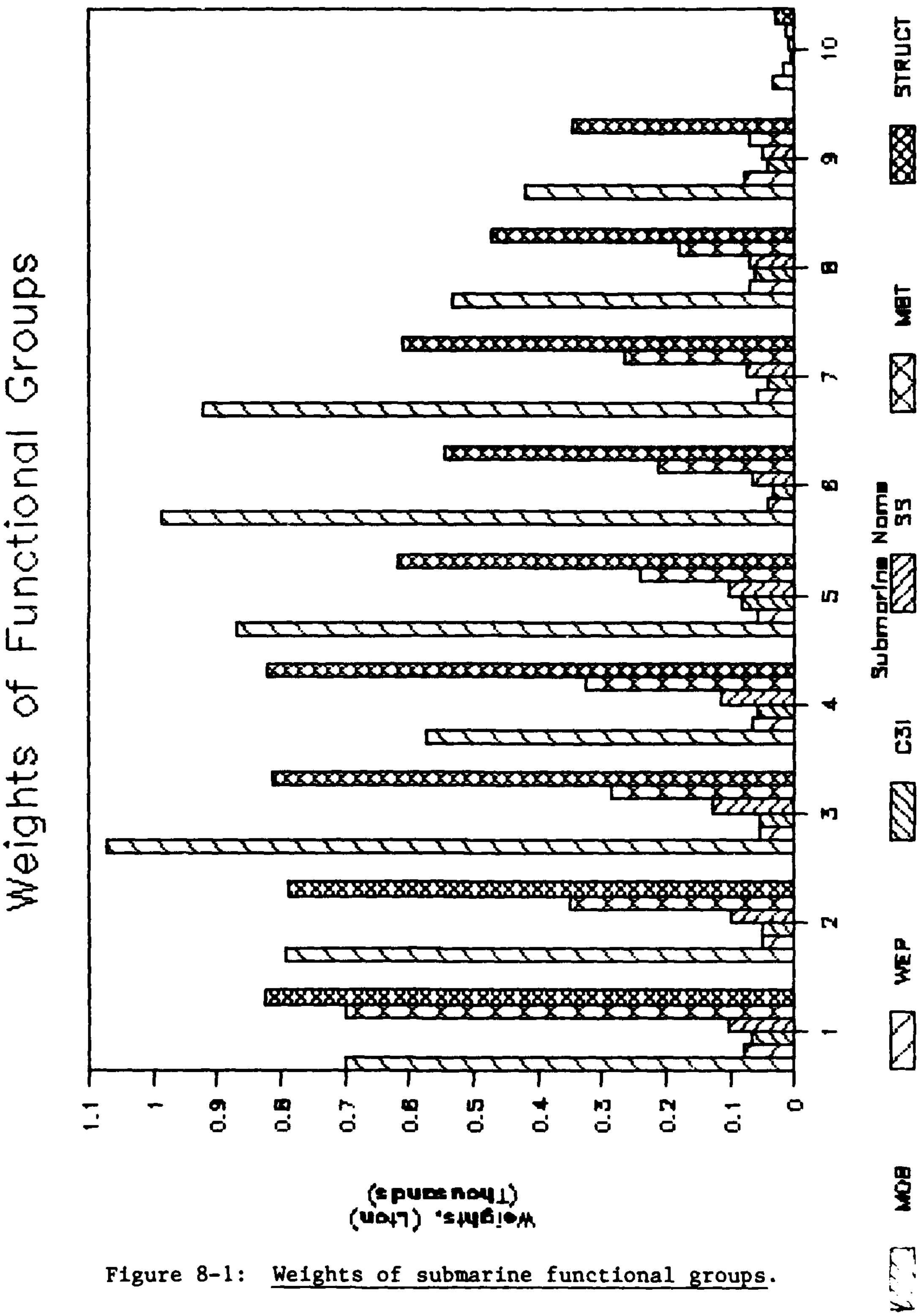


Figure 8-1: <u>Weights of submarine functional groups.</u>

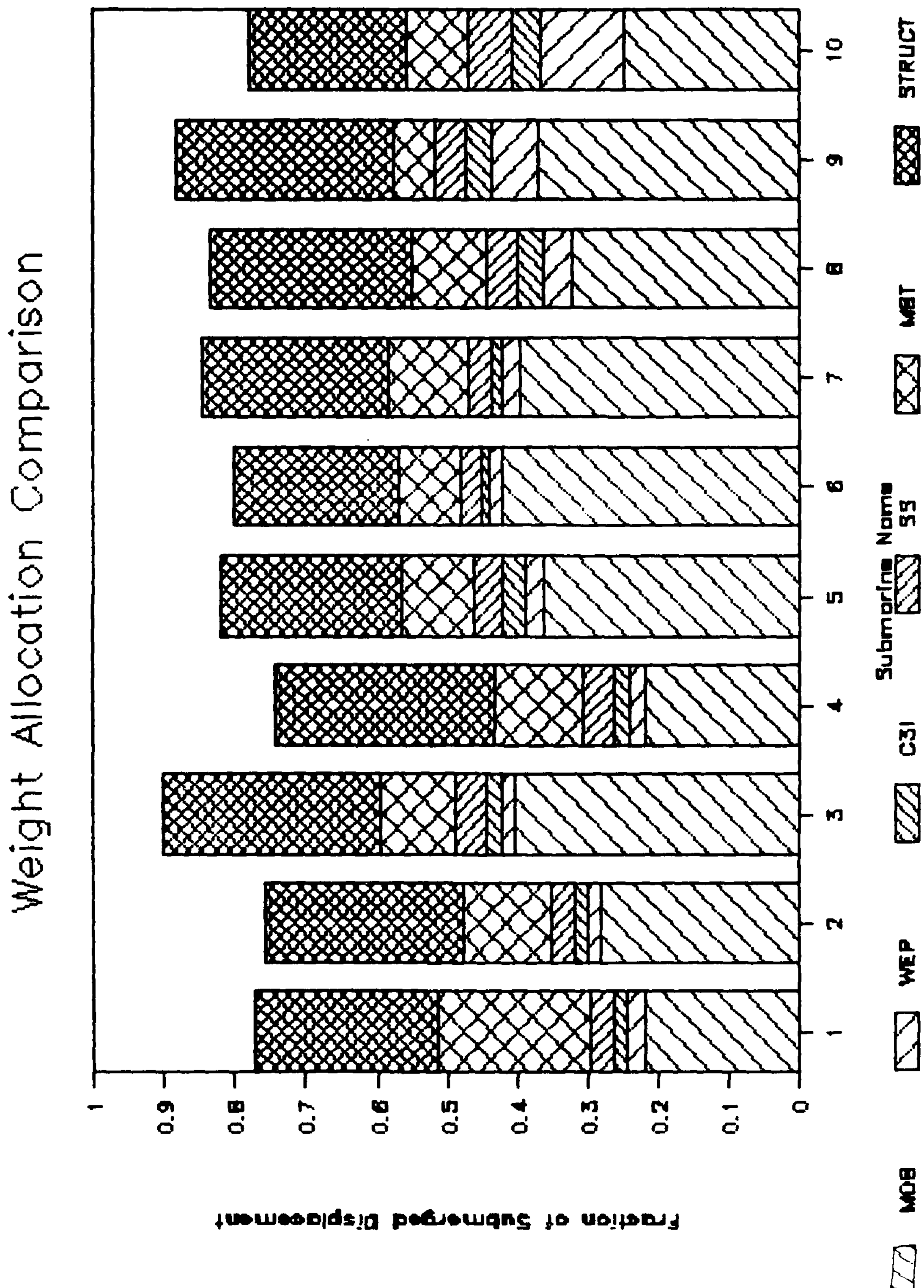


Figure 8-2: Submarine weight allocation comparison.

Chapter 8

MILITARY PERFORMANCE

8.1 Propulsion and Mobility

The speed, range, and depth capabilities of a submarine are three of its prime attributes, and high values for each of these parameters is desirable, as they allow the submarine to act with greater flexibility, and hence, greater effectiveness. Specific values of these parameters are not available in the literature for the range of speeds of which these submarines are capable. This section focuses upon developing such a comprehensive database. Public-domain data germane to the mobility functional area is summarized in Table 9-1.

8.1.1 Required Shaft Horsepower

The study commences with calculations of the maximum sustained speed of each submarine. Extensive analysis of each submarine's propulsion characteristics are performed in this study. Computer models of the hydrodynamic envelope are established in Appendix B, and used to calculate the shaft horsepower required at various speeds at deep and snorkel depths in Appendices C and D. The resulting values of required shaft horsepower at deeply submerged depths are shown in Figure 9-1. while the ratio of the larger shaft horsepower required when operating at snorkel depth is depicted in Figure 9-2.

Figure 9-1 shows the characteristic cubic dependency of the power upon speed. for a body moving in a viscous medium without the generation of gravity waves.

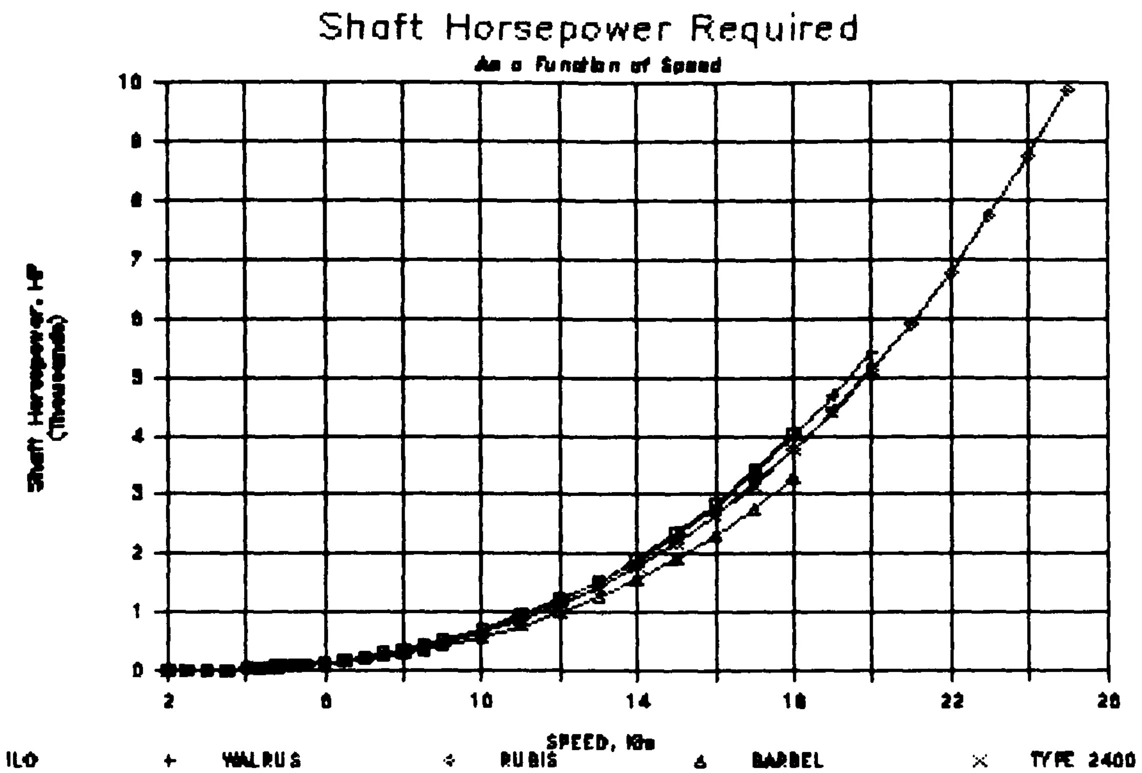
Figure 9-2 indicates humps and other irregularities in the speed/power curve for operation at a depth where gravity waves are generated. The irregularities are caused

PROPULSION AND MOBILITY	KILO	REF	WALRUS	REF	RUBIS	REF	BARBEL	REF	TYPE 2400	REF
	SUBMARINE NAME									
SUBMRGD SPD, Ref	25	(17)	?		25	(17)	21	(17)	20	(32)
SUBMRGD SPD, Calc	18		20		25.1		17.8		20.5	
SURFACE SPEED	12	(17)	12	(7)	20	(17)	15	(17)	12	(32)
SNORT SPEED	10	(e)	12	(7)	N/A		10	(e)	10	(32)
SHP INSTALLED, HP	4000	(17)	5360	(7)	10000	(e)	3150	(17)	5400	(17)
ALTERNATOR CAP, KW	4480	(e)	5170		370	(e)	3580		2500	(32)
DIESEL CAP, HP	6000	(e)	6930	(11)	500	(e)	4800	(17)	3618	(32)
HOTEL LOAD, Kw	124.5		124.7		129.7		94.38		115.9	
BUNKER FUEL, Lton	270	(e)	275	(e)	19.4		130	(e)	186.7	(32)
IMMERSION, Meters	300	(e)	300	(24)	300	(10)	120	(e)	200	(5)
NR OF MAIN MOTORS:	2	(e)	1	(5)	1	(17)	2	(17)	1	(5)
EMERGENCY MOTOR?	YES	(e)	YES	(e)	YES	(8)	YES	(e)	YES	(e)
FWD PLANE POSIT	SAIL	(e)	SAIL	(24)	SAIL	(8)	SAIL	(35)	HULL	(13)
STERN PLANE FORM	CROSS	(e)	"X"	(24)	CROSS	(8)	CROSS	(35)	CROSS	(13)
BOW THRUSTER?	NO	(e)	NO	(24)	NO	(e)	NO	(35)	NO	(13)
NUMBER OF CELLS	480	(e)	480	(7)	120	(e)	504	(35)	480	(32)
WEIGHT, Lton	275	(e)	275		68.75	(e)	290		275	(32)
VOLUME, cu ft	4000	(e)	4007		1000	(e)	5700		4675	
HIGH-END VOLTAGE	590	(e)	590	(e)	276	(e)	580	(e)	590	(32)
LOW-END VOLTAGE	440	(e)	440	(e)	228	(e)	479	(e)	440	(32)
BATTERY ENERGY	KW-Hrs		KW-Hrs		KW-Hrs		KW-Hrs		KW-Hrs	
@ 100 Hr Rate	11280		11280		2820		11844		11280	

Table 9-1: Propulsion plant and other mobility group parameters. (Sheet one of two).

	SUBMARINE NAME									
PROPULSION AND MOBILITY	TYPE 1700	REF	TYPE 2000	REF	SAURO	REF	VASTER- GOTL'D	REF	MIDGET 100	REF
SUBMRGD SPD, Ref	25	(7)	25	(6)	19.3	(12)	?		18	(33)
SUBMRGD SPD, Calc	24.7		25		19.3		20		16.8	
SURFACE SPEED	13	(7)	13	(6)	11	(12)	11	(17)	8	(e)
SNORT SPEED	15	(7)	15	(6)	11	(12)	10	(e)	N/A	(33)
SHP INSTALLED, HP	8844	(7)	7500	(6)	4207	(12)	2537		420	(29)
ALTERNATOR CAP, KW	4400	(7)	3600	(6)	2160	(12)	2000		90	
DIESEL CAP, HP	6000		5400	(6)	2894	(12)	2680	(19)	120	(29)
HOTEL LOAD, Kw	114.9		108.2		88.13		63.88		15	(1)
BUNKER FUEL, Lton	319	(7)	236	(6)	144	(12)	40		7.668	
IMMERSION, Meters	300	(7)	325	(5)	300	(12)	300	(e)	200	(29)
NR OF MAIN MOTORS:	1	(7)	1	(e)	1	(12)	1	(e)	1	(29)
EMERGENCY MOTOR?	YES	(e)	YES	(e)	YES	(e)	YES	(e)	48HP	(29)
FWD PLANE POSIT	SAIL	(2)	HULL	(e)	SAIL	(12)	SAIL	(36)	SAIL	(33)
STERN PLANE FORM	CROSS	(2)	CROSS	(e)	CROSS	(12)	"X"	(36)	CROSS	(33)
BOW THRUSTER?	NO	(2)	NO	(e)	NO	(12)	NO	(36)	YES	(33)
BATTERY CELLS	960	(e)	720	(5)	296	(5)	168	(7)	13	(e)
BATTRY WGT, Lton	550		412.5		170		96.25		8.6	
BATTRY VOL, cu ft	9989		7013		2371		1509		90	
BATTRY VOLT (HIGH)	590	(e)	590	(e)	680.8	(e)	420	(19)	29.9	
BATTRY VOLT (LOW)	440	(e)	440	(e)	562.4	(e)	285	(19)	24.7	
BATTERY ENERGY @ 100 Hr Rate	KW-Hrs 22560		KW-Hrs 16920		KW-Hrs 6956		KW-Hrs 3948		KW-Hrs 305.5	

Table 9-1: Propulsion plant and other mobility group parameters. (Sheet two of two).



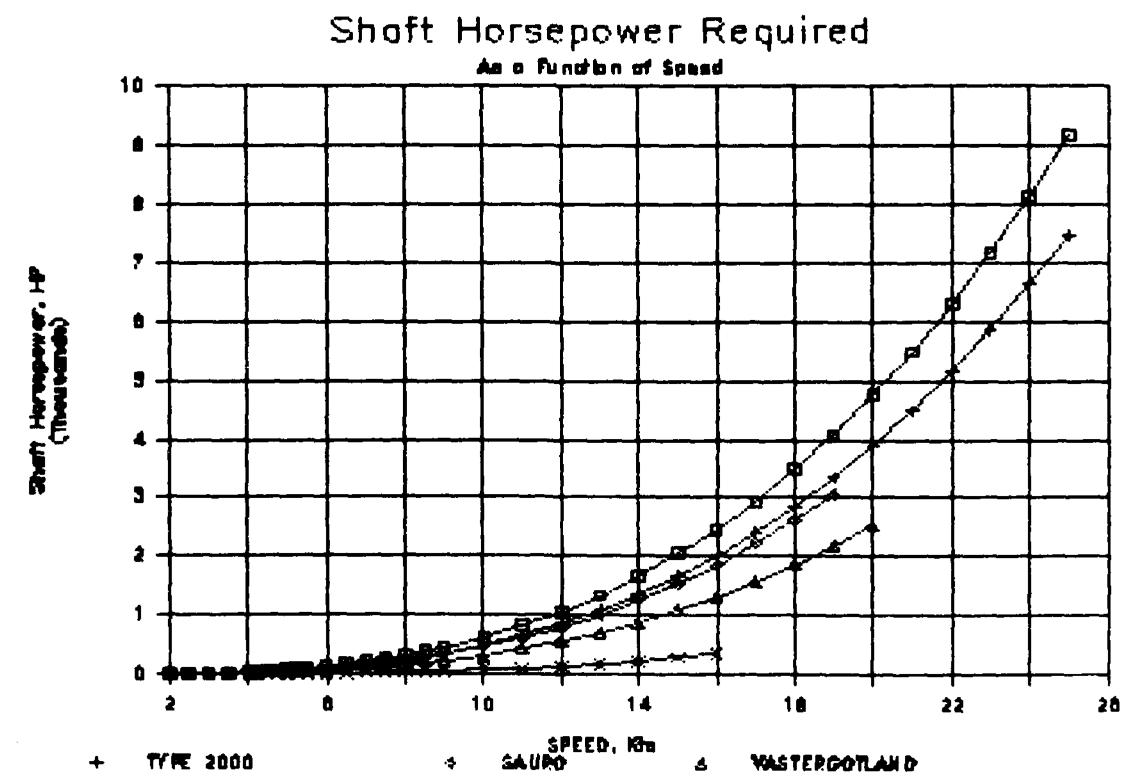
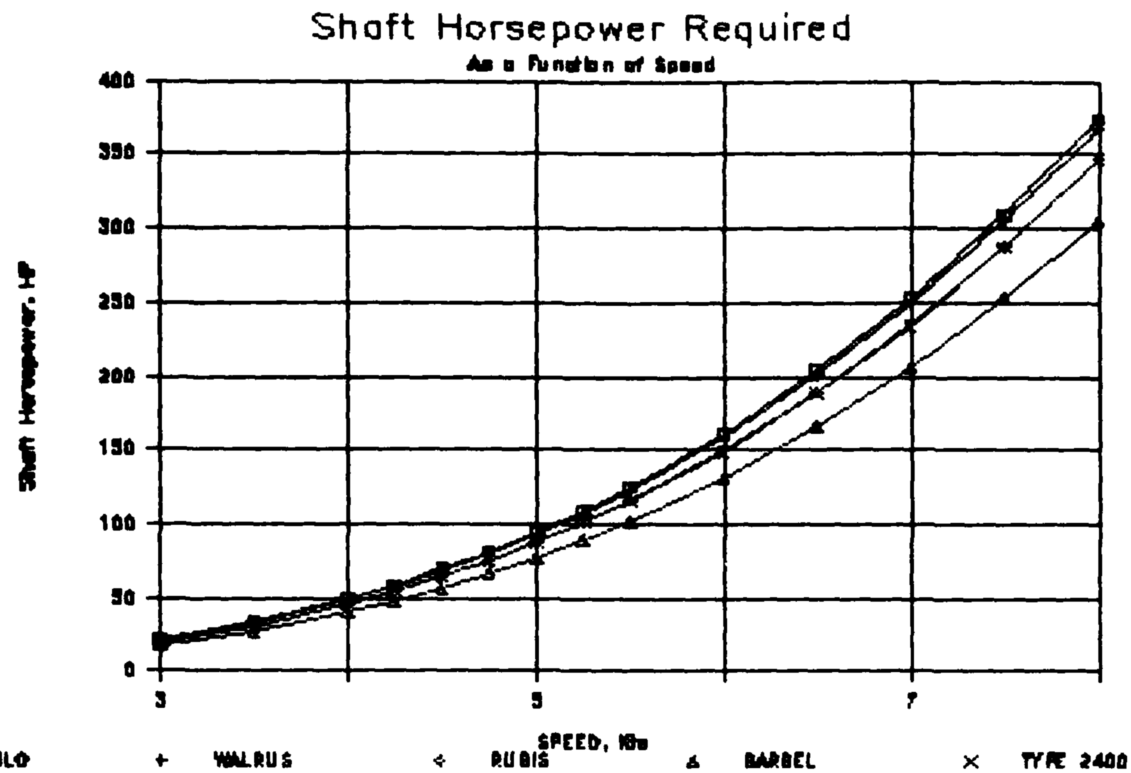


Figure 9-1: Required Shaft Horsepower at various speeds. (Sheet 1 of 2)



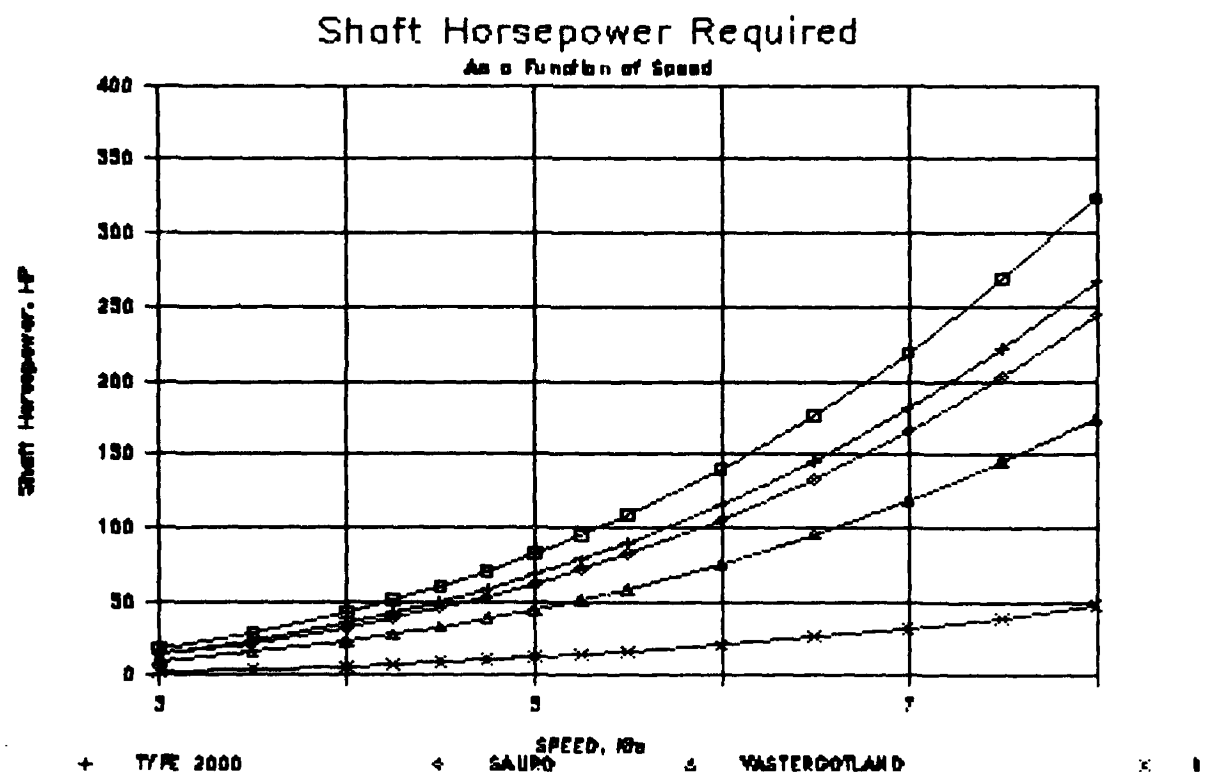
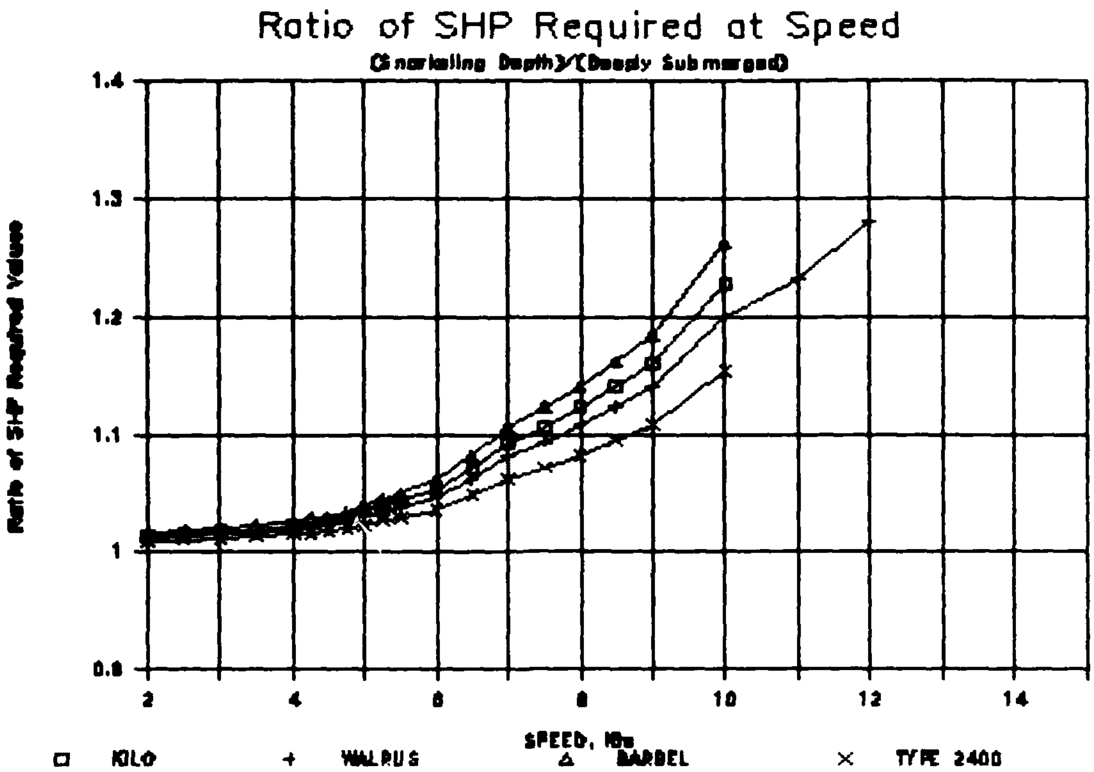


Figure 9-1: Required Shaft Horsepower at various speeds. (Sheet 2 of 2)



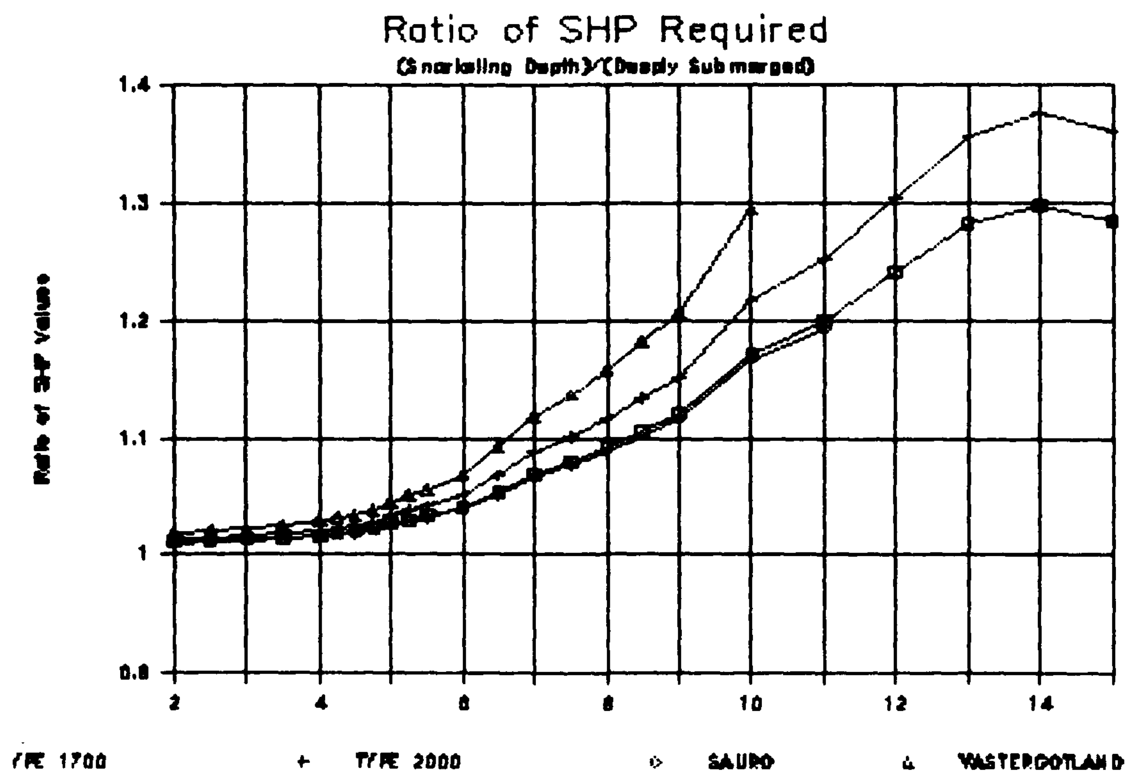


Figure 9-2: Ratio of SHP required at Snorkel Depth to SHP required at Deep Submergence Depth.

as the generated waveform alternately hinders to a greater extent, then to a lesser extent, then to a still greater extent, the progress of the submarine through the water. This wave drag may be predicted as a function of Froude Number, and submergence ratio, according to the method of Appendix D.

8.1.2 Fuel Endurance Range

The endurance range based upon bunker fuel load is calculated in Appendix E, and the results are displayed in Figure 9-3.

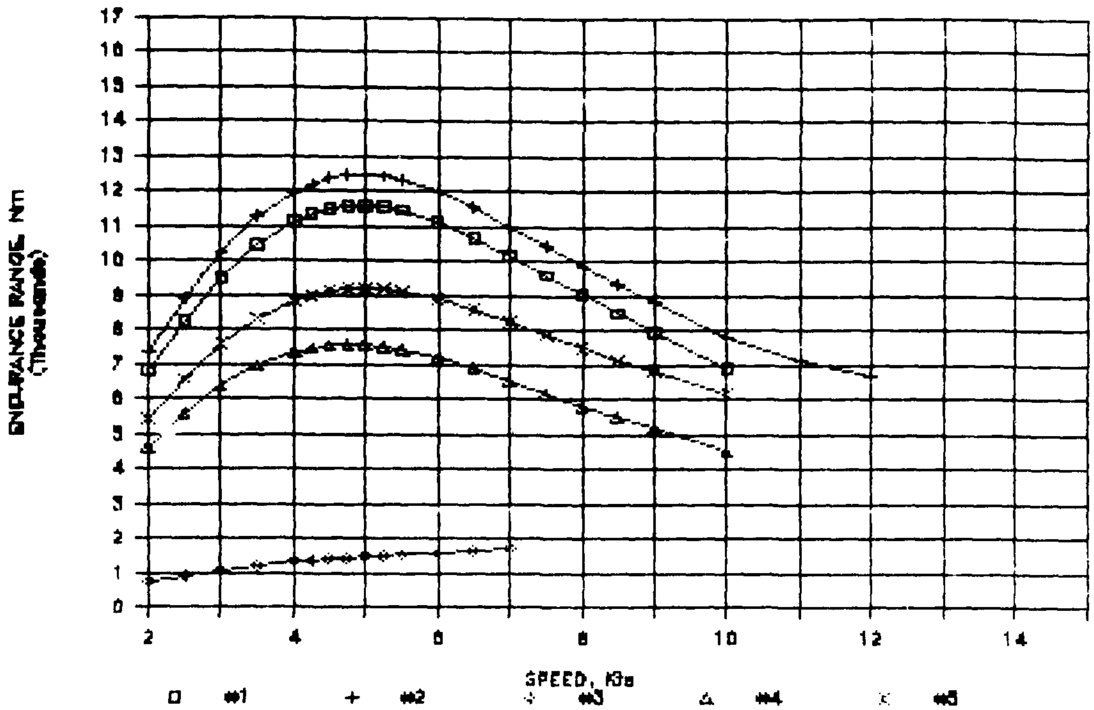
This is in general quite a lengthy range, since the submarines are loaded with enough fuel to travel goodly distances at higher speeds, and the speed for maximum fuel endurance is usually in the vicinity of four or five knots. The fuel endurance range is not the final word on endurance range for the submarine, considering all factors, but it is an excellent way to compare designs in the area of hull efficiency and amount of bunker fuel loaded. The fuel endurance range is calculated conservatively, using the value of SHP at snorkel depth, since much of the transit would be accomplished under this operating condition.

There is an economy of scale concerning range. Since the SHP required is a function of the wetted surface area of the submarine, and since the amount of diesel fuel (or the number of battery cells, or the number of days of provisions), which can be carried is a function of the internal volume of the submarine, then the endurance range of a submarine will increase for increasing displacement, all else being equal.

To compensate for its low endurance range, the MIDGET 100 is equipped with a bow-mounted towing cable, which would allow it to be deployed from a mothership when within a manageable range of the operating area.

Appendix E gives a relation for calculating the optimum speed for maximizing fuel endurance range.

Snorkeling/Fuel Endurance Range



Snorkeling/Fuel Endurance Range

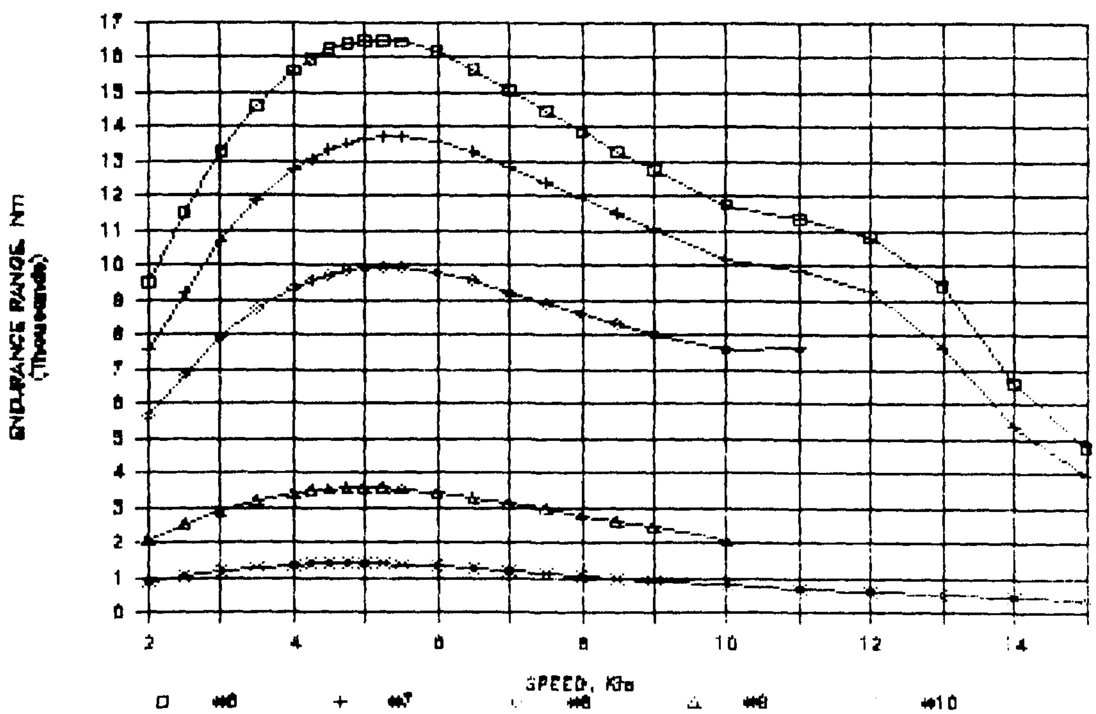


Figure 9-3: Endurance range based upon fuel load, at snorkel depth.

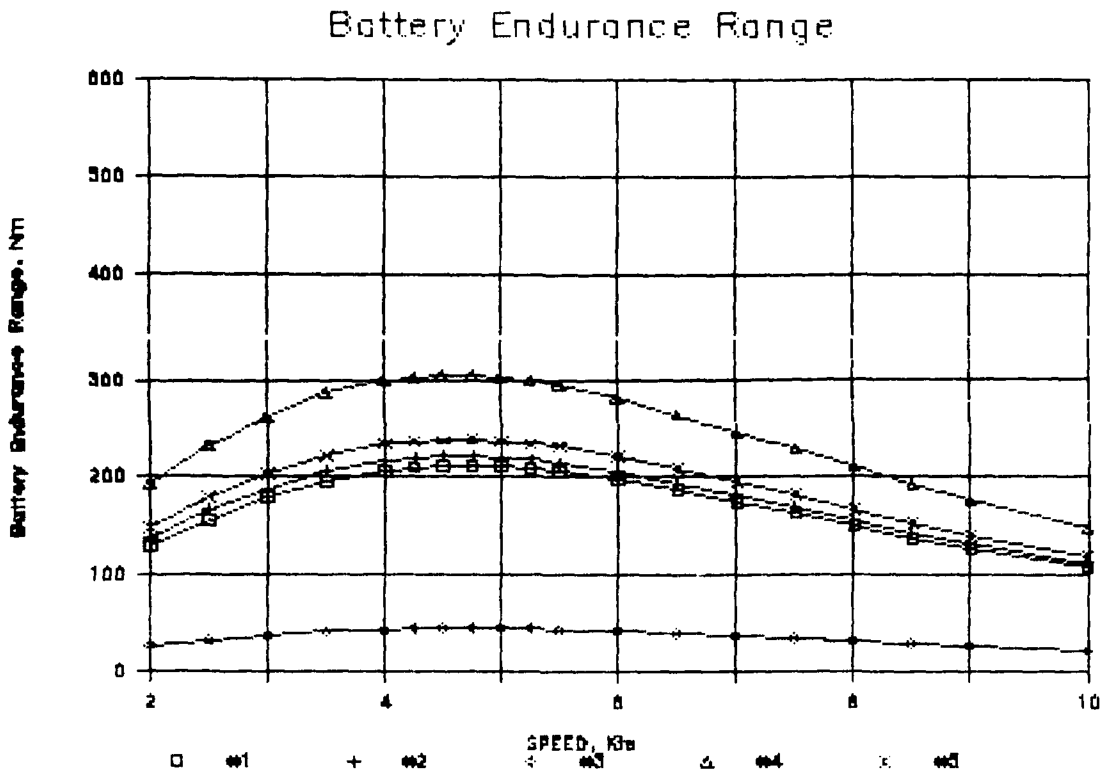
8.1.3 Battery Endurance Range

The battery endurance range is calculated in much the same way that the fuel endurance range is calculated, except that the source of power is the storage battery instead of diesel fuel. Battery endurance range is of great importance militarily, since the submarine may travel much more quietly on electric motor than on snorkeling diesel, and is also much less susceptible to radar and infrared detection than when snorkeling. The problem with calculating battery endurance range is that the available energy to propel the submarine decreases as the rate of demand for it (the power level) is increased. This is due to the fact that at high power rates, as much as forty-percent of the stored chemical energy is dissipated as heat, and is unavailable for useful work. Further discussion of this is contained in Appendix F.

The calculation of the battery endurance range is conducted in Appendix G, and the resulting plot is shown in Figure 9-4. An inspection of Figure 9-4 reveals the advantage of outfitting a submarine with a large battery, when submerged endurance counts. The tremendous battery range of the TYPE 1700 is due primarily to its very large battery, and also to its moderate hotel load and required shaft horsepower.

RUBIS has a low battery endurance range because it is equipped with a small battery. MIDGET 100 has a very small battery, and a relatively high hotel load as well. Both of these subs have primary propulsive power which is independent, to a degree, of the atmosphere, and so the need to avoid snorkeling is not present. RUBIS and MIDGET 100 presumably have a battery just large enough allow them to operate stealthily for a short mission, perhaps just enough power to operate hotel services while remaining as a silent sentry or picket at bare steerageway.

The RUBIS has a nuclear reactor to generate steam for the turbo-alternators, which produce electric power for the main propulsion motor and hotel electricity.



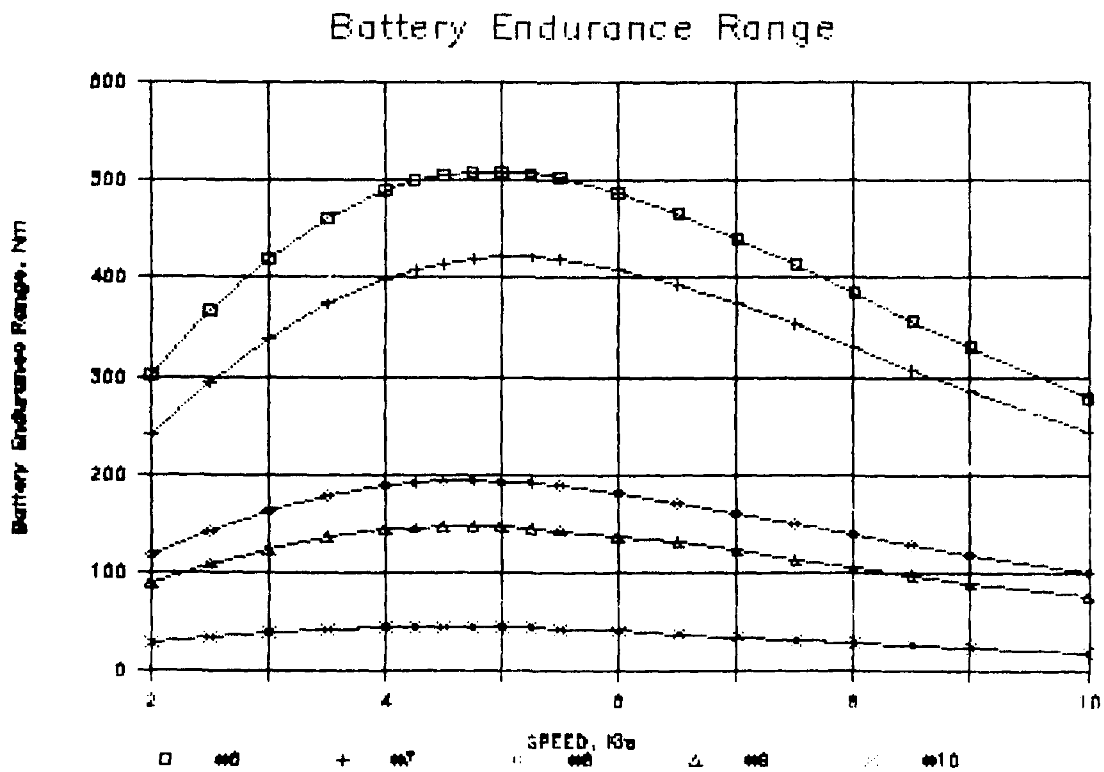
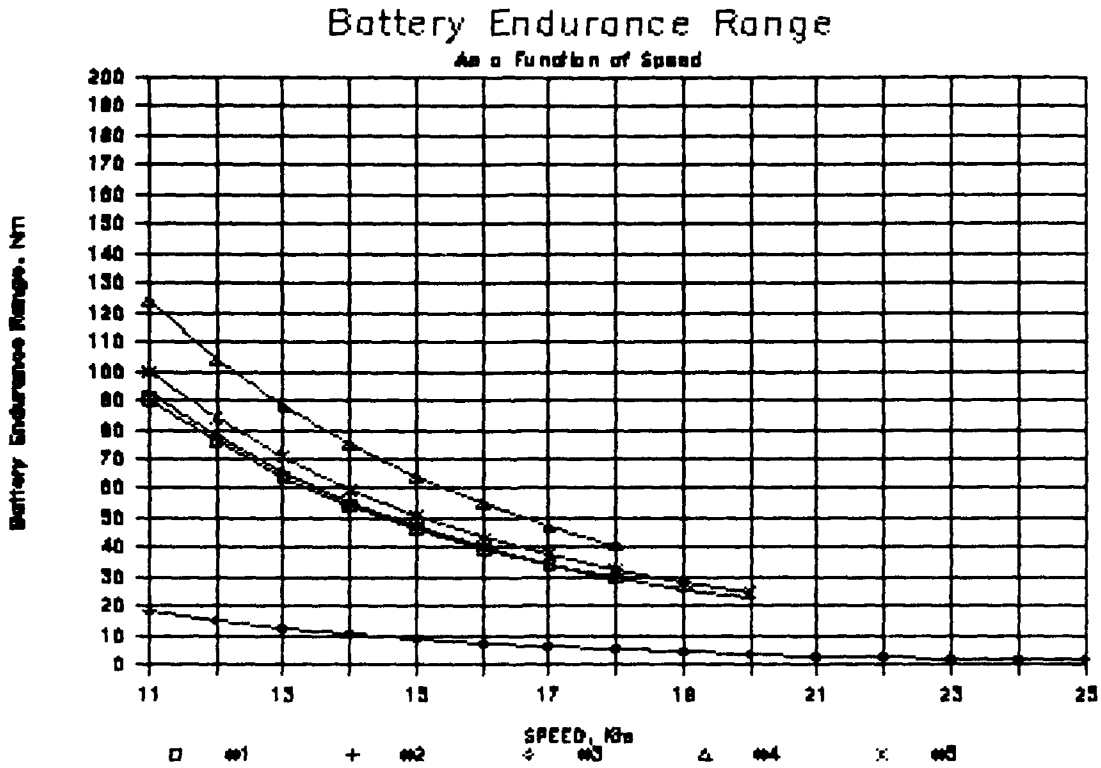


Figure 9-4: Endurance range based upon battery capacity. (Sheet 1 of 2) 80% DoD.



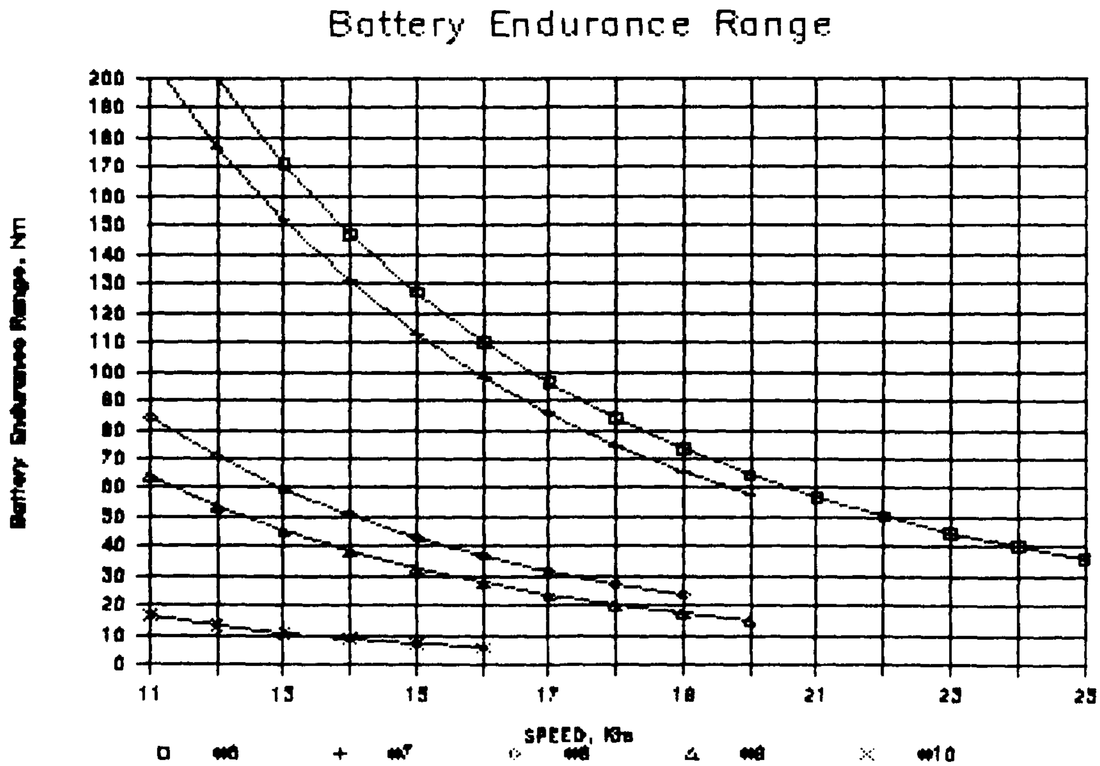


Figure 9-4: Endurance range based upon battery capacity. (Sheet 2 of 2) 80% DoD.

The MIDGET 100 has a closed-cycle diesel main propulsion engine clutched to the main shaft. There are also two smaller closed-cycle diesel alternator sets, which supply hotel electric, charge the battery, and can supply the emergency electric propulsion motor.

8.1.4 Indiscretion Rate and Interval

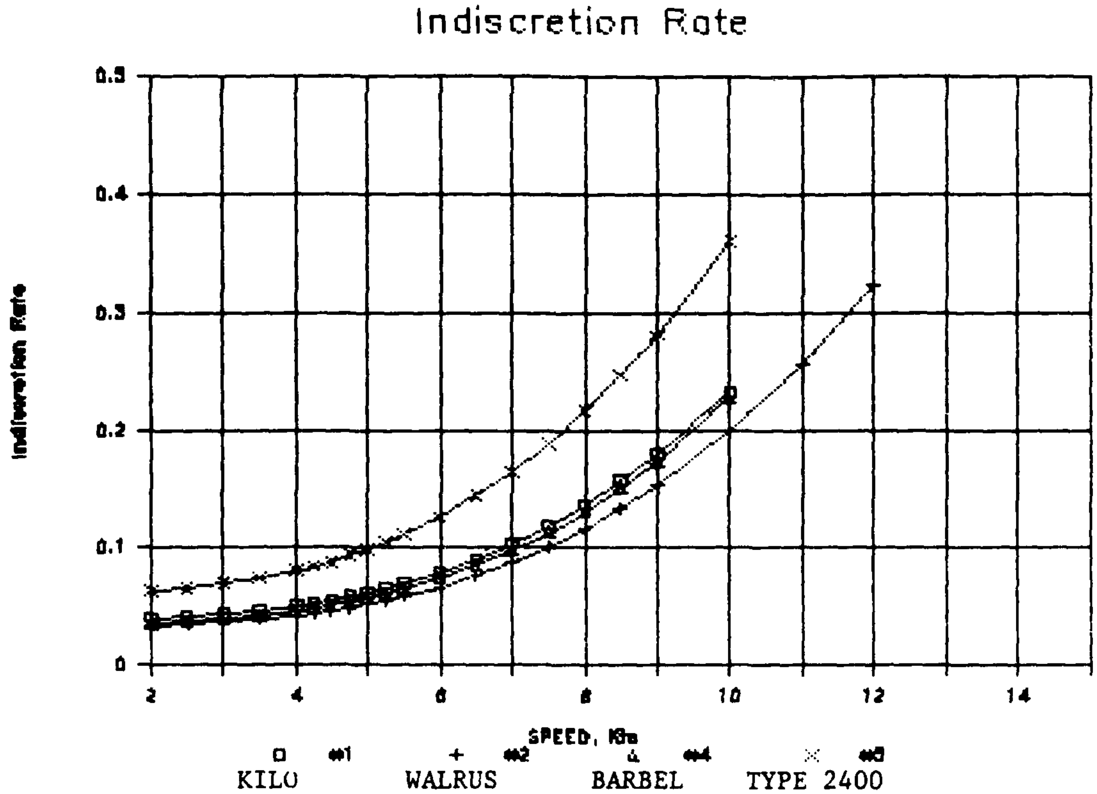
Indiscretion rate, evaluated at a particular speed, is the fraction of time which a submarine must spend snorkeling, in order to charge its battery. Indiscretion interval, evaluated at a particular speed, is the duration of time which elapses between indiscretion periods.

The indiscretion rates of each of the submarines is calculated in Appendix H, and is displayed for the range of snorkel-capable speeds in Figure 9-5. As expected, the submarines with large batteries and large alternator capacities have the lowest indiscretion rates for a given speed. As discussed in Appendix H, the alternator capacity is very important in keeping indiscretion rate low, because the recharging time is less. However, there is a limit to the recharging rate, since the same type of inefficiency exists in recharging the battery as in drawing power from it.

The indiscretion interval is also discussed and computed in Appendix H, and the results are shown in Figure 9-6. For very low speeds, the indiscretion interval becomes much greater, then tapers off to a maximum. The batteries of all of the submarines benefit from being operated at a lower power level, which frees up more available energy, and accentuates the already increasing indiscretion interval.

8.1.5 Overall Endurance Range

For the purposes of this study, overall endurance range shall be defined as the range the submarine can achieve at constant speed, all factors considered. In other words, when the submarine exhausts one set of supplies, be it fuel, water, provisions, or



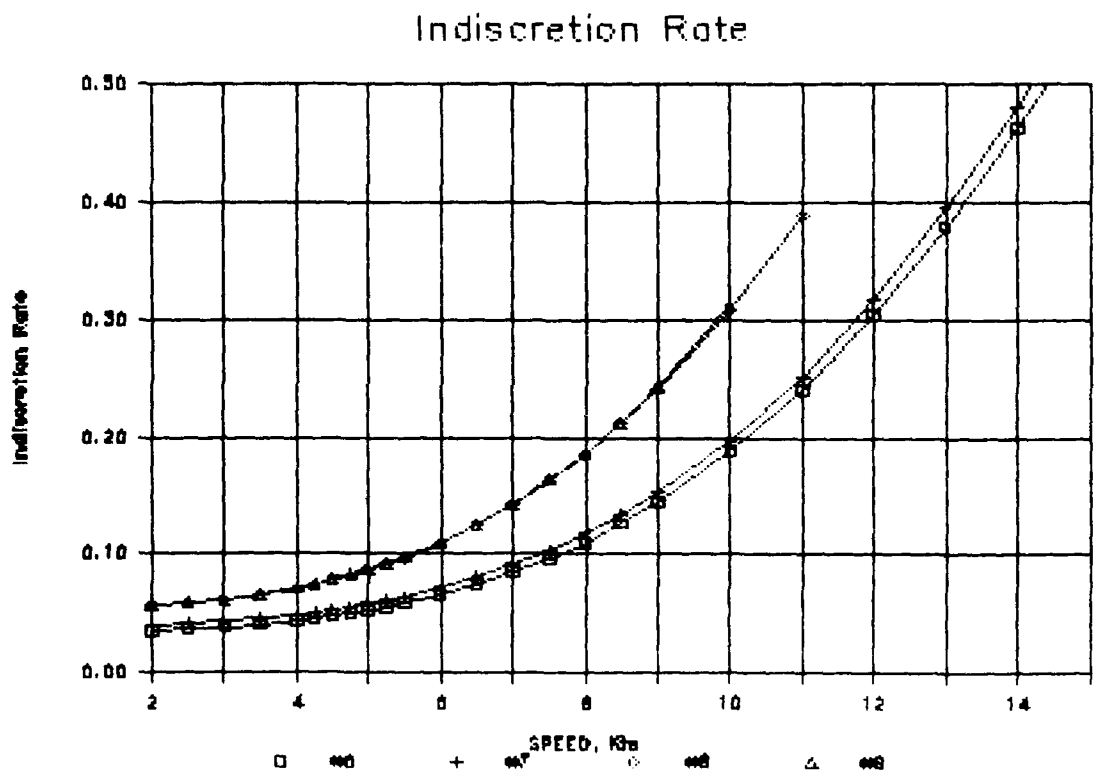
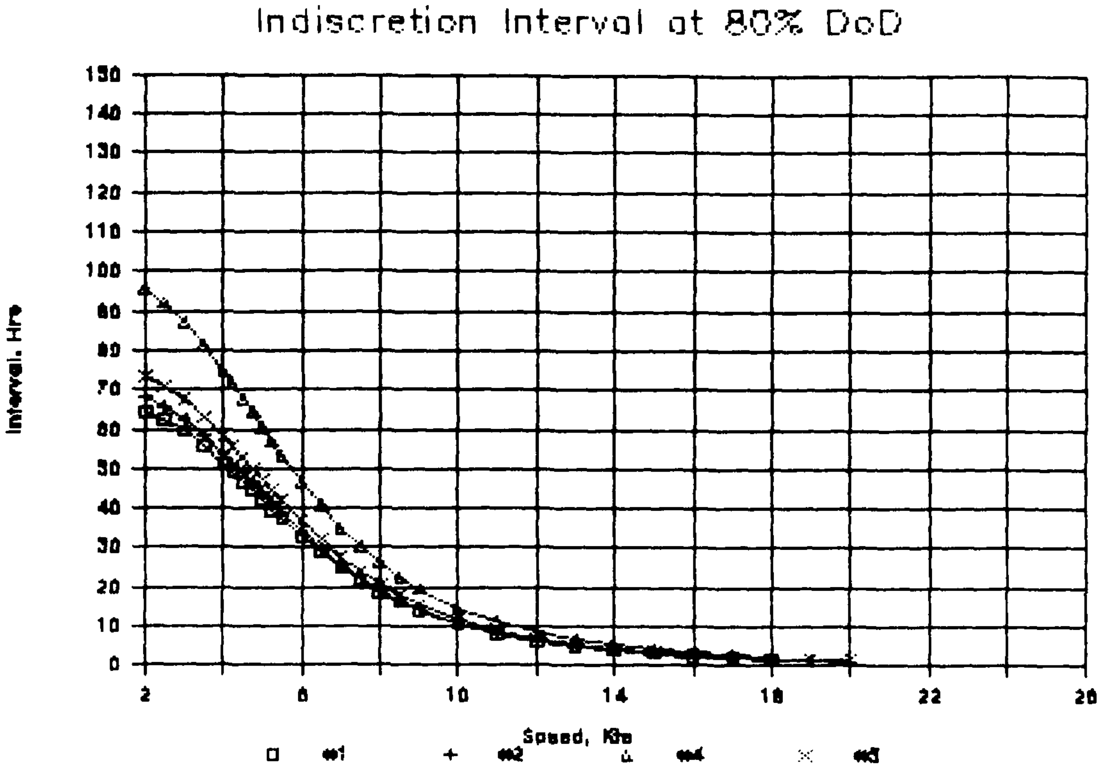


Figure 9-5: Indiscretion rate at snorkeling speeds, 80% DoD.



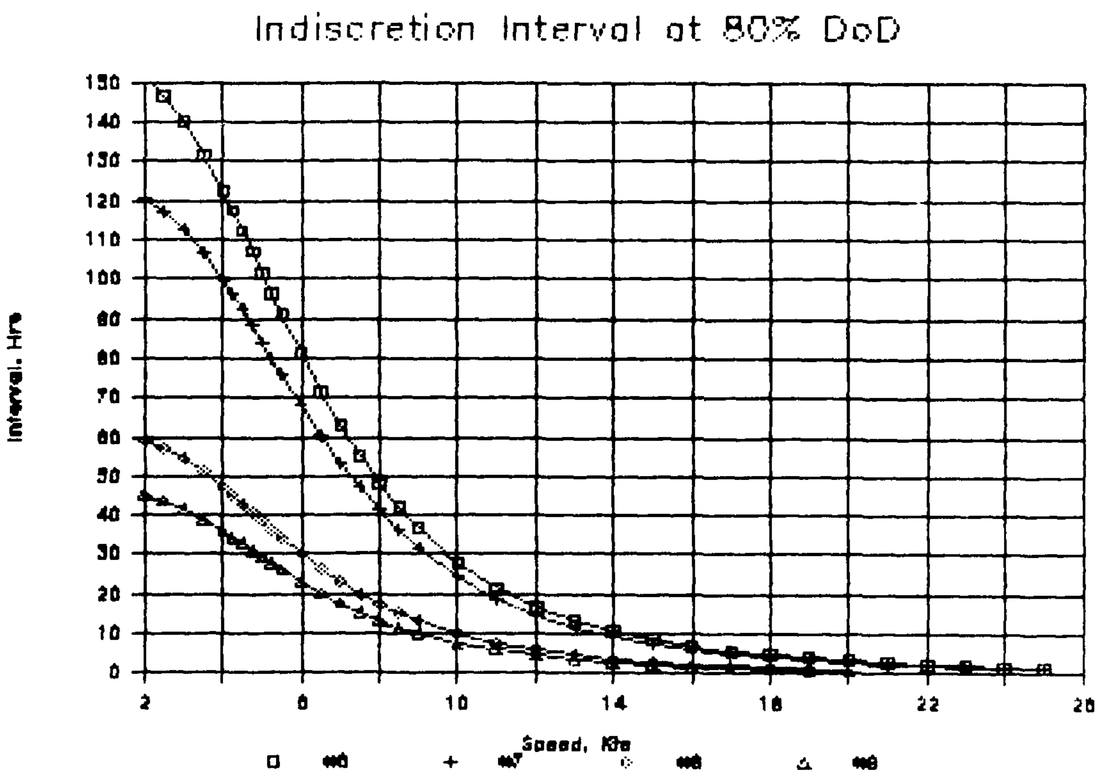


Figure 9-6: Indiscretion interval at snorkeling speeds, 80% DoD.

battery, it has completed its journey, and its range at that speed is defined as the length of that journey. However, battery range does not figure into overall range, since the battery may be recharged as long as there is fuel remaining. So overall range will depend upon whether provisions or fuel are exhausted first at a given speed.

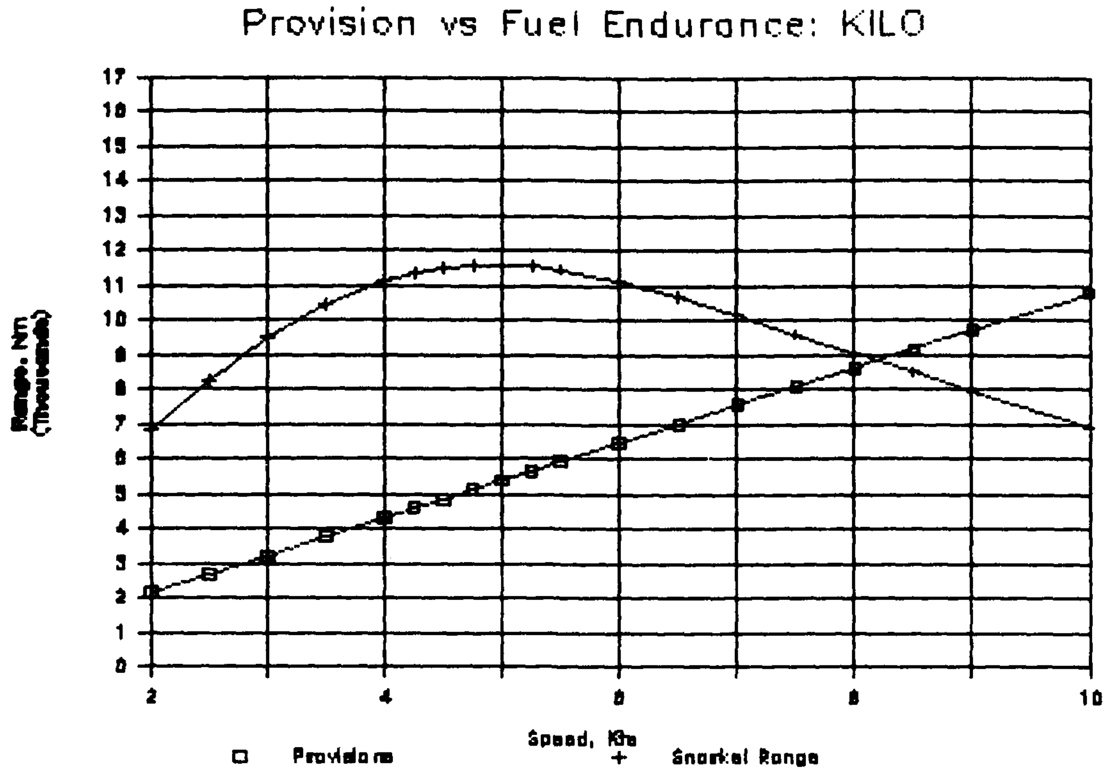
Figure 9-7 shows plots of provision and fuel range for speeds between two and ten knots. Provision range is directly proportional to the vessel speed, since the time rate of provision consumption is assumed constant. If a submarine were to be designed solely to maximize endurance range at a constant speed, then ideally provisions and fuel would be exhausted simultaneously, at the speed of best fuel endurance range. Real diesel-electric submarines usually need extra fuel since they may need to conduct high-speed actions which require more fuel per mile. As such, Figure 9-7 reveals that nearly all of the conventionally-powered boats have provision ranges less than their fuel range at the optimum fuel range speed. This indicates a deliberate loading of additional fuel to allow the overall range to be increased, and for it to occur at a greater speed.

For the nuclear-powered RUBIS, the overall range is normally taken as the provision range. The fuel range on emergency diesel, with 100% expenditure of bunker fuel, is shown in Figure 9-7 for comparison.

8.2 Weapons Systems

8.2.1 Weapons Launching Systems

The number, length, diameter, and launching method of a submarine's torpedo tubes are important military parameters. They determine the size and type of weapon which may be employed by the submarine. The number of torpedo tubes is related to the number of weapons which may be fired in a salvo, and perhaps also to the fire rate. Whether a submarine has the ability to track multiple targets and direct multiple weapons to those targets was not available in the open literature.



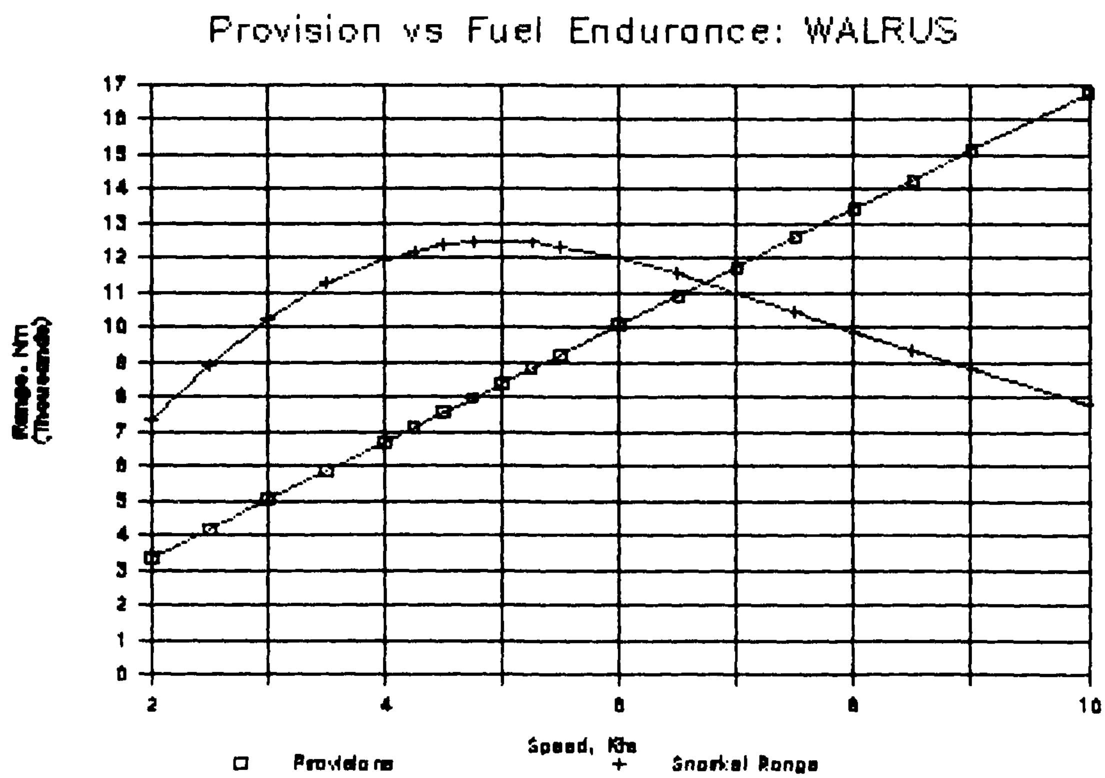
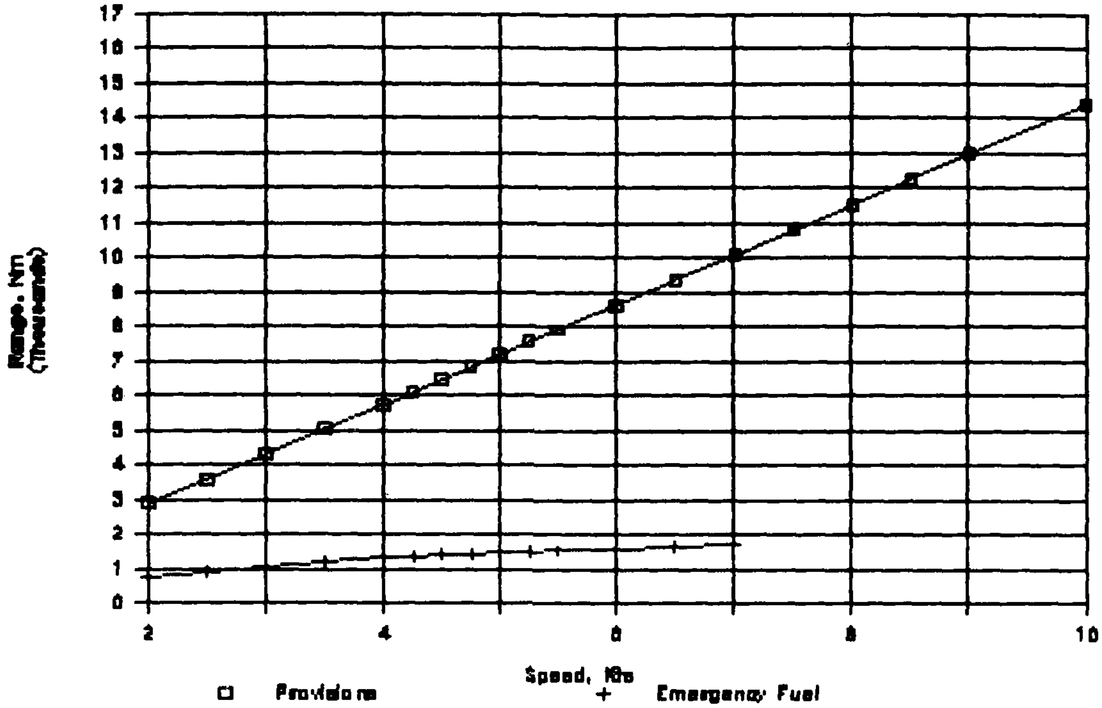


Figure 9-7; Provision Endurance plotted with Fuel Endurance. (Sheet 1 of 5)

Provision vs Emergency Fuel: RUBIS



Provision vs Fuel Endurance: BARBEL

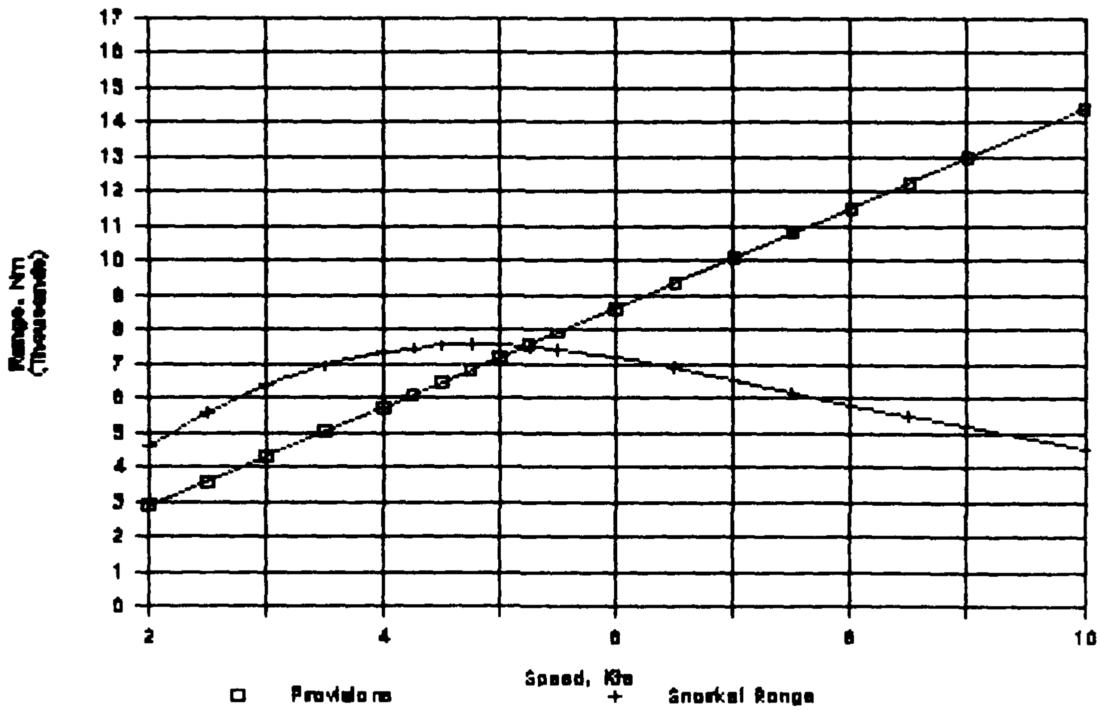
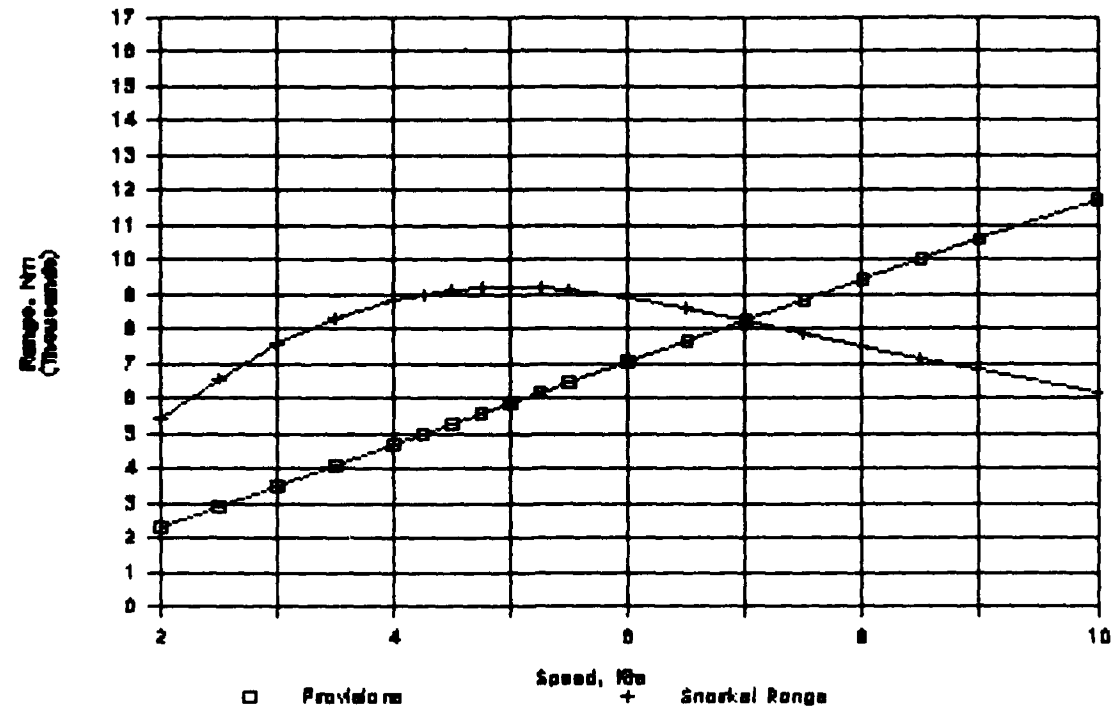


Figure 9-7: <u>Provision Endurance plotted with Fuel Endurance</u>. (Sheet 2 of 5)

Provision vs Fuel Endurance: TYPE 2400



Provision vs Fuel Endurance: TYPE 1700

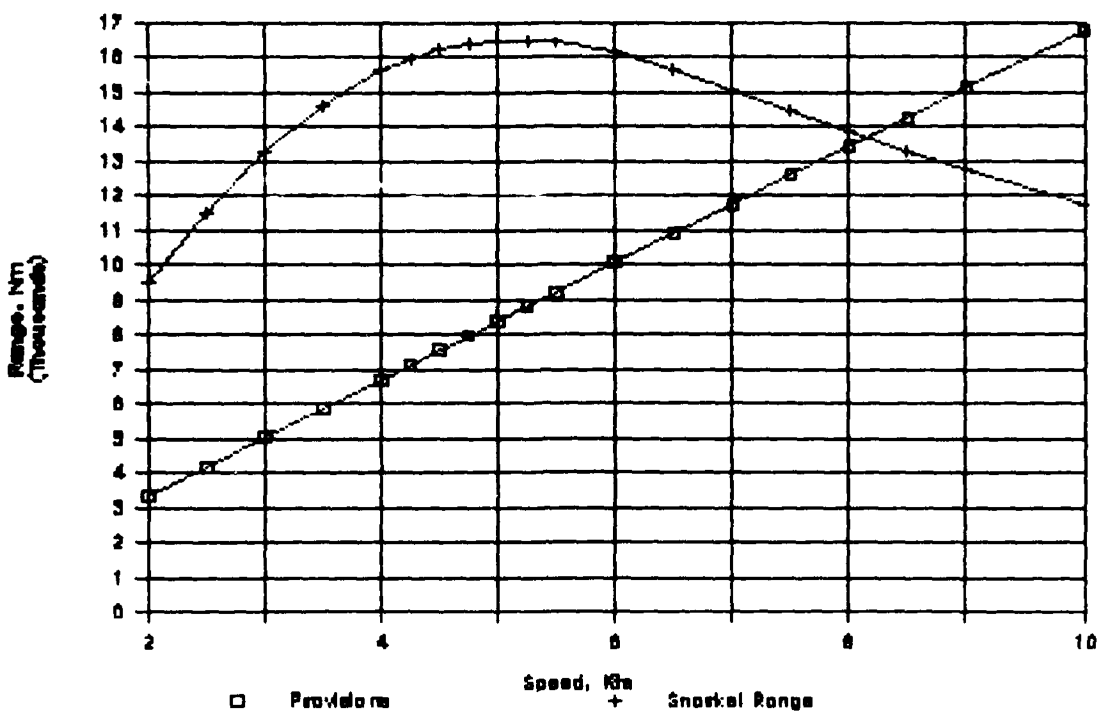
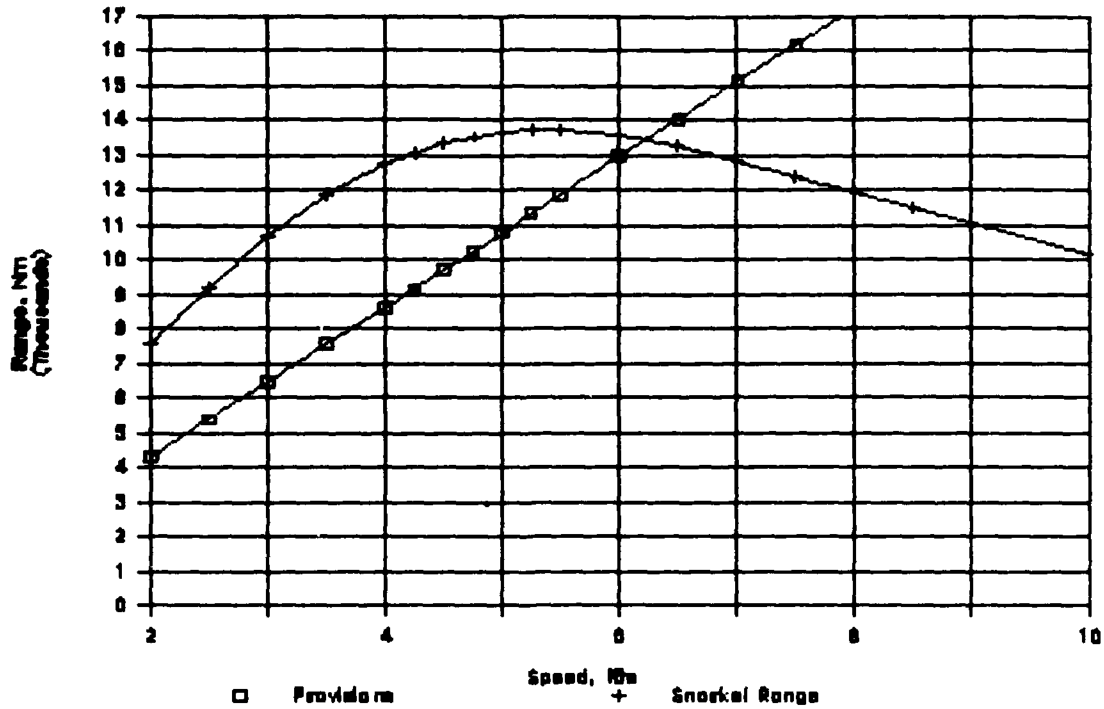


Figure 9-7: Provision Endurance plotted with Fuel Endurance. (Sheet 3 of 5)

Provision vs Fuel Endurance: TYPE 2000



Provision vs Fuel Endurance: SAURO

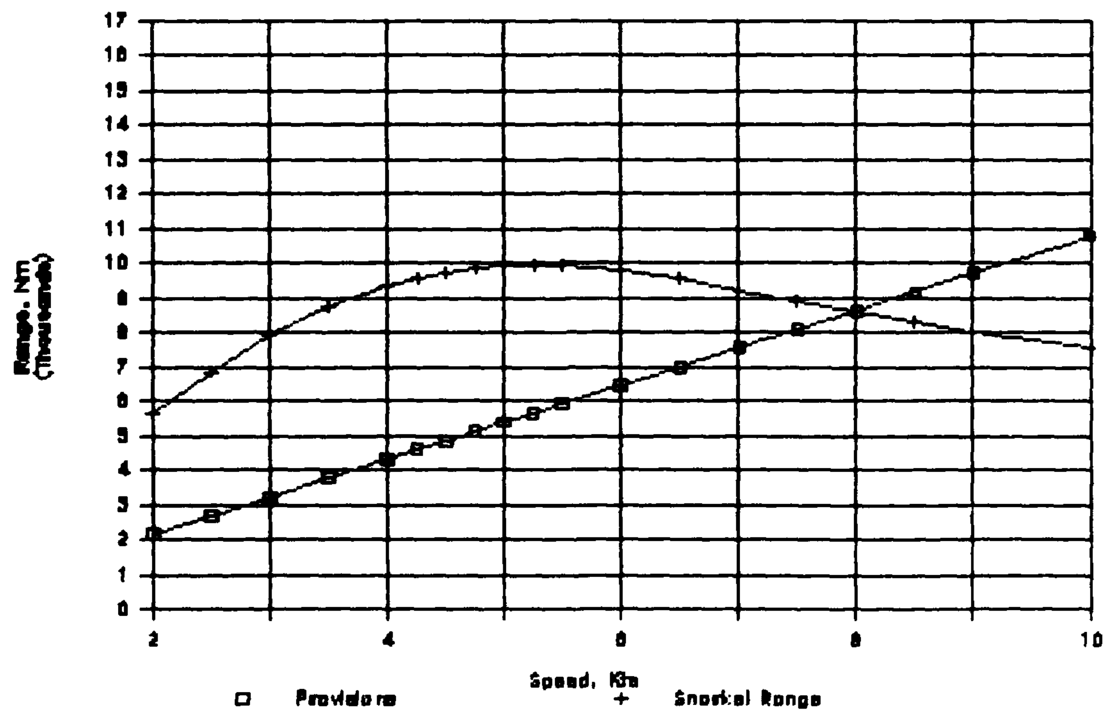
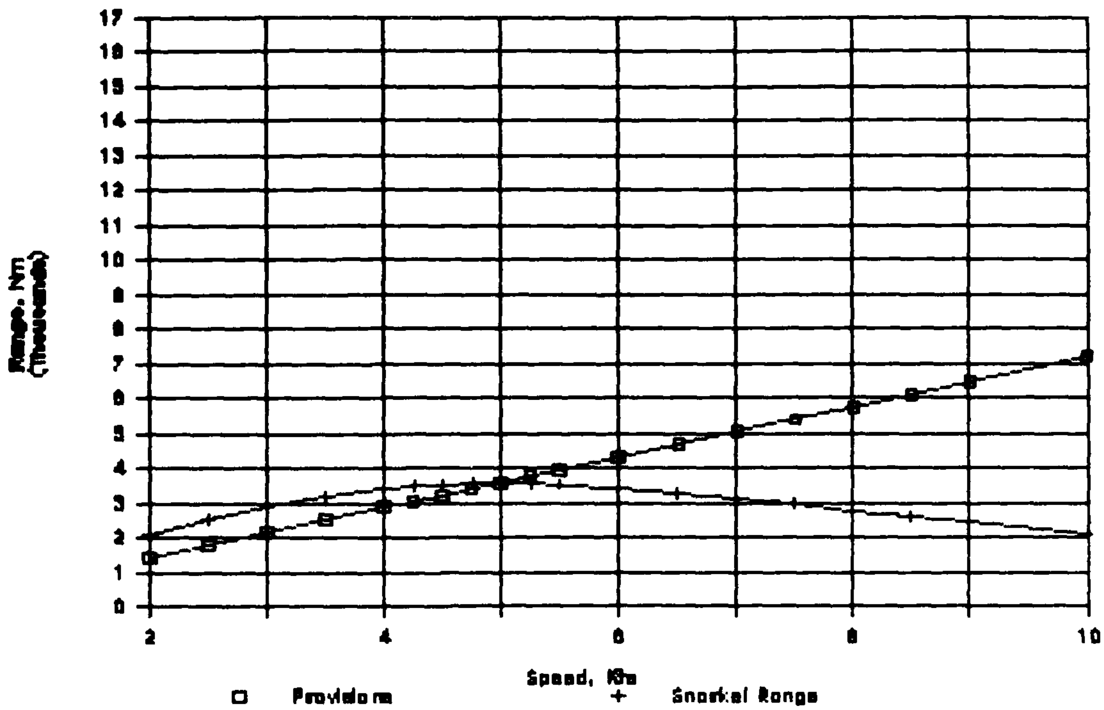


Figure 9-7: Provision Endurance plotted with Fuel Endurance. (Sheet 4 of 5)

Provision vs Fuel Endurance: VASTERG'ND



Provision vs Fuel Endurance: MIDGET 100

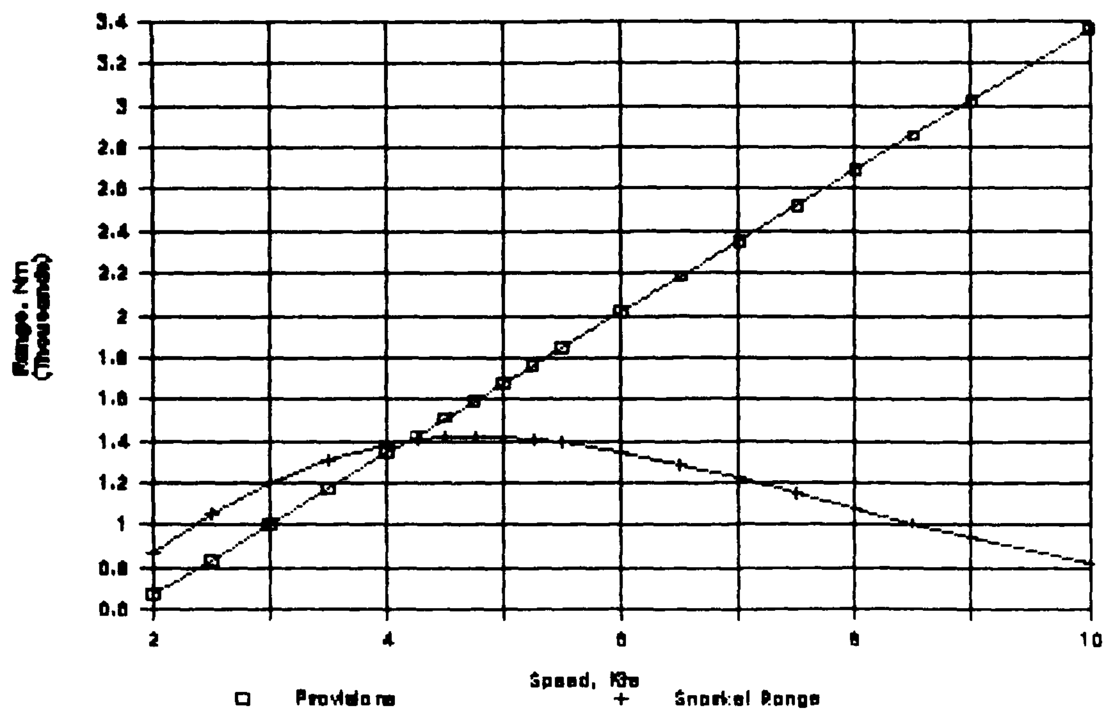


Figure 9-7: Provision Endurance plotted with Fuel Endurance. (Sheet 5 of 5)

The launching system is important because it determines whether cruise missiles may be fired from the torpedo tubes. At this time, nothing was found in the open literature to state that swim-out encapsulated cruise missiles have been developed, so any submarine not using some type of positive ejection system to launch weapons cannot employ cruise missiles. It is the author's opinion however, that self-launching cruise missiles may be in development.

The standard tube diameter in the West is 21 inches (533mm) which will accomodate the heavyweight torpedoes and encapsulated cruise missiles made in the West. Lightweight torpedoes are 15 inches in diameter, and are carried on surface ships, aircraft and some smaller submarines, such as the MIDGET 100.

Table 9-2 lists weapons systems parameters. The term "Water Slug" is used to denote a positive ejection launch mechanism, although the details of the exact type were not found in the literature. Note that KILO, WALRUS, RUBIS, BARBEL, and TYPE 2400 employ positive ejection methods while the remaining five do not.

Evaluating the combat systems effectiveness of a submarine based upon the number of tubes and reload torpedoes possessed is tricky. On one hand, the assumption could be made that all torpedo tubes have equal fire and reload rates, and that each submarine can compute and maintain fire control solutions for as many targets and torpedoes as it is equipped with torpedo tubes. In this scenario, advantage clearly belongs to the submarine with the most tubes. On the other hand, it could be assumed that a designer equips a given submarine with an abundance of tubes because of anticipated poor tube reliability, or poor weapon kill probability. In actuality, there is not enough data in the open literature to make a detailed evaluation of the combat systems effectiveness. For the purposes of this study, it shall be assumed that all torpedo tubes have equal fire and reload rates, and that each submarine can compute and maintain fire control solutions for half as many targets and torpedoes as it is equipped with torpedo tubes.

WEAPONS SYSTEMS PARAMETER	KILO	REF	WALRUS	REF	RUBIS	REF	BARBEL	REF	TYPE 2400	REF
PRIMARY TORP TUBES	8	(17)	4	(7)	4	(10)	6	(35)	6	(32)
OTHER TUBES	0	(17)	0	(7)	0	(10)	0	(35)	0	(32)
NUMBER OF RELOADS	10	(17)	20	(17)	10	(10)	6	(35)	12	(32)
TUBE DIAM, (in)	21	(e)	21	(7)	21	(17)	21	(35)	21	(32)
TORPEDO LAUNCH METHOD	WATER SLUG	(e)	WATER SLUG	(16)	WATER SLUG	(e)	WATER SLUG	(e)	WATER SLUG	(32)
TORPEDO NAME			MK-48	(22)	F17P	(22)	MK-48	(22)	SPEARFISH	
TORPEDO SPEED, Kts	50	(e)	55	(22)	40	(e)	55	(22)	70	(22)
WARHEAD WGT, Kg	300	(e)	300	(22)	250	(22)	300	(22)	180	(e)
TORPEDO RANGE, Km	40	(e)	45	(22)	40	(e)	45	(22)	45	(22)
CRUISE MISSILES?	YES	(e)	YES	(17)	YES	(22)	YES	(e)	YES	(22)
MAX NMBR CARRIED	18	(e)	24	(17)	14	(17)	12	(e)	18	(e)
MISSILE NAME	SSN-21	(26)	UGM-84	(17)	SM-39	(22)	UGM-84	(e)	UGM-84	(22)
MISSL RANGE, Km	125	(e)	125	(e)	50	(17)	125	(e)	125	(e)
WARHEAD WGT, Kg	150	(e)	150	(e)	125	(17)	150	(e)	150	(e)
MINE-LAYING?	YES	(23)	YES	(e)	YES	(e)	YES	(e)	YES	(32)
MAX NMBR CARRIED	20	(e)	40	(e)	20	(e)	12	(e)	24	(e)
WHERE CARRIED	WITHIN	(e)	WITHIN	(e)	WITHIN	(e)	WITHIN	(e)	WITHIN	(32)
DEPLOYMENT METHOD	TUBES	(e)	TUBES	(e)	TUBES	(e)	SELF	(e)	TUBES	(32)
WARHEAD WGT, Kg	600	(e)	600	(e)	600	(e)	300	(e)	600	(e)
SWIMMERS CARRIED?	YES	(e)	NO	(e)	NO	(e)	NO	(e)	YES	(32)
AIRLOCK CAPACITY	3	(e)	N/A	(e)	N/A	(e)	N/A	(e)	5	(32)
SWIMMER CHARIOTS?	NO	(e)	NO	(e)	NO	(e)	NO	(e)	NO	(e)
MAX NMBR POSSIBLE	N/A	(e)	N/A	(e)	N/A	(e)	N/A	(e)	N/A	(e)
AAW ROCKETS	MAYBE	(17)	NO	(e)	NO	(e)	NO	(e)	NO	(e)
NUMBER	?	(17)	N/A	(e)	N/A	(e)	N/A	(e)	N/A	(e)
GUNS	NO	(e)	NO	(e)	NO	(e)	NO	(e)	NO	(e)
CALIBER	N/A	(e)	N/A	(e)	N/A	(e)	N/A	(e)	N/A	(e)

Table 9-2: Weapons Systems parameters. (Sheet one of two).

WEAPONS SYSTEMS PARAMETER	TYPE 1700	REF	TYPE 2000	REF	SAURO	REF	VASTER-GOTL'D	REF	MIDGET 100	REF
PRIMARY TORP TUBES	6	(7)	8	(5)	6	(5)	6	(36)	4	(1)
OTHER TUBES	0	(7)	0	(5)	0	(5)	3	(36)	0	(1)
NUMBER OF RELOADS	16	(7)	12	(5)	6	(5)	6	(36)	0	(29)
TUBE DIAM, (in)	21+	(7)	21+	(e)	21	(5)	21B,15	(36)	15+	(33)
TORPEDO LAUNCH METHOD	SWIM OUT	(7)	SWIM OUT	(5)	SWIM OUT	(12)	SWIM OUT	(36)	SWIM OUT	(1)
TORPEDO NAME	SEAL	(22)	SEAL	(22)	A184	(22)	TP617	(22)	(LWT)	(33)
TORPEDO SPEED, Kts	35+	(22)	35+	(22)	50	(e)	60	(22)	40	(e)
WARHEAD WGT, Kg	260	(22)	260	(22)	250	(e)	250	(22)	50	(1)
TORPEDO RANGE, Km	35+	(22)	35+	(22)	28	(22)	70	(e)	12	(e)
CRUISE MISSILES?	NO	(e)	NO	(e)	NO	(e)	NO	(e)	NO	(e)
MAX NMBR CARRIED	N/A	(e)	N/A	(e)	N/A	(e)	N/A	(e)	N/A	(e)
MISSILE NAME	N/A	(e)	N/A	(e)	N/A	(e)	N/A	(e)	N/A	(e)
MISSL RANGE, Km	N/A	(e)	N/A	(e)	N/A	(e)	N/A	(e)	N/A	(e)
WARHEAD WGT, Kg	N/A	(e)	N/A	(e)	N/A	(e)	N/A	(e)	N/A	(e)
MINE-LAYING?	YES	(e)	YES	(e)	YES	(e)	YES	(36)	YES	(29)
MAX NMBR CARRIED	32	(e)	24	(e)	12	(e)	22	(e)	10	(29)
WHERE CARRIED	WITHIN	(e)	WITHIN	(e)	WITHIN	(e)	PODS	(7)	PODS	(29)
DEPLOYMENT METHOD	SELF	(e)	SELF	(e)	SELF	(e)	SELF	(7)	PLACED	(29)
WARHEAD WGT, Kg	300	(e)	300	(e)	300	(e)	600	(e)	600	(29)
SWIMMERS CARRIED?	YES	(31)	YES	(31)	NO	(e)	NO	(e)	NO*	(29)
AIRLOCK CAPACITY	3	(e)	3	(e)	N/A	(e)	N/A	(e)	N/A	(29)
SWIMMER CHARIOTS?	NO	(e)	NO	(e)	NO	(e)	NO	(e)	NO*	(29)
MAX NMBR POSSIBLE	N/A	(e)	N/A	(e)	N/A	(e)	N/A	(e)	N/A	(29)
AAW ROCKETS	YES	(31)	NO	(e)	NO	(e)	NO	(e)	NO	(e)
NUMBER	4	(31)	N/A	(e)	N/A	(e)	N/A	(e)	N/A	(e)
GUNS	NO	(e)	NO	(e)	NO	(e)	NO	(e)	YES	(1)
CALIBER	N/A	(e)	N/A	(e)	N/A	(e)	N/A	(e)	40mm&20mm	

Table 9-2: Weapons Systems parameters. (Sheet two of two).

8.2.2 Torpedoes

Torpedoes have been the weapon of choice for submarine use. Although much slower than guns or missiles, the torpedo is employed very effectively by submarines because of the submarine's stealth. Because the torpedo warhead explodes beneath the surface of the water, it is more damaging to the hull structure of a surface vessel than an equally-sized missile warhead.

There are several heavyweight torpedoes manufactured in the West, all of which are compatible with the free-world submarines of this study. All are effective weapons within their firing envelopes. The size of the envelope is the important criteria, and is governed by the speed, range, and depth capabilities, by the onboard sensing and logic systems, and by the presence or absence of a datalink to the parent submarine. Superior speed is needed to overtake the target, the rule of thumb being twice the anticipated target speed, Reference (14). Sufficient range and depth capabilities are also necessary to complete the pursuit, and the sonar and logic circuits aboard the torpedo are important for terminal guidance. The datalink (such as wire-guidance) with the mother sub is important for mid-course guidance.

Perhaps the most capable heavyweight torpedo in the West is the MK-48 ADCAP, Reference (14), primarily because of its speed, range, and depth capability, the exact values of which are classified. However, the torpedo parameters listed in Table 9-2 are suitable for comparison.

8.2.3 Cruise Missiles

The capability of a submarine to carry cruise missiles gives the it the medium-range (50 nautical mile) stand-off attack mode against surface targets which was previously the province of only surface ships and attack aircraft. Only those submarines equipped with a positive ejection system (and the requisite fire control electronics) may currently employ cruise missiles. Fire control solutions would most likely be gained by passive array sonar, which may have ranges up to 45 kilometers or more, the exact values being classified.

The ability of a submarine to carry cruise missiles is clearly an advantage. For those ships able to employ them, encapsulated cruise missiles may be loaded in lieu of heavyweight torpedoes on a one-for-one basis.

8.2.4 Mine Laying

A submarine, particularly a diesel-electric submarine, is ideally equipped because of its stealth to conduct covert mining operations. Many offensive mining scenarios call for covert placement of the mines. In general, two small mines may be loaded in lieu of one heavyweight torpedo. Table 9-2 lists mine laying parameters. Submarines not equipped with positive ejection tubes must employ self-propelled mines. Kockums Shipyard, manufacturer of the VASTERGOTLAND, has developed an external mine-belt conveyance system, the advantage of which is that a full load of mines may be carried without affecting the torpedo load.

8.2.5 Other Weapons Systems

The use of combat swimmers for reconnaisance and other activities is believed to be a primary mission area of some diesel-electric submarines. It is known that the TYPE 2400, TYPE 1700, and TYPE 2000 submarines are equipped with swimmer lockout chambers, detailed in Table 9-2. KILO is judged by the author to have this capability as well. A variant of the MIDGET 100 is constructed with a four-person swimmer lockout chamber instead of the four lightweight torpedo tubes. The MIDGET 100 may also tow swimmer delivery vehicles to the operating area, but this must reduce its endurance range.

KILO may be equipped with anti-air missiles mounted in the fairwater. These may have been installed in response to the high state of aircraft-based anti-submarine warfare (ASW) capabilities among NATO forces.

MIDGET 100 is equipped with a 20mm and a 40 mm deck gun. This further indicates that the primary mission area of this vessel is special operations.

8.3 Command, Control, Communication, and Information

8.3.1 Sonar

The primary sensor of the modern submarine is passive sonar. The structure of the sonar may be conformal hull-mounted array, trailed linear array, or spherical, cylindrical bow-mounted array, or a composite sensing system made up of several of these arrays. The advantage of passive sonar is that the submarine can remain undetected while observing its environment. A submarine with a passive sonar is able to determine the bearing of a sound source. When equipped with a sensitive conformal or trailed linear array, the submarine can get range information as well from the time delay in reception of the incident sound waves. With range and bearing information, the computation of fire control solutions is possible.

Active sonar is usually used tactically to confirm the computed target range by a single active "ping" immediatly prior to weapon launch. It is typically at this point that opposing sonar-equipped vessels, both surface ships and other submarines, first become aware of the sub's presence. For reasons of stealth, active sonar is not often used by a submarine on patrol.

The quintessential parameter of sonar performance is sensitivity. Sensitivity and discrimination, to be able to detect a potential target and separate its sound from the ambient noise in order to verify its existence and possibly its identity. The detection range is dependent upon the sensitivity of the sonar, and detectability is the "name of the game" when stealth and first-strike capability are of paramount importance. Unfortunately, because of its importance, detection capabilities of sonar equipment is not available in the literature. The literature does have information on the manufacturers, and in some cases the particular model, of the various sonars installed in the subject submarines, as may be seen in Table 9-3. All of the submarines in this study are equipped with both active and passive sonar, and most have a towed linear or flank conformal array sonar as well.

8.3.2 Periscopes

The traditional submarine sensor is the periscope. Modern periscopes are equipped with telescopes, rangefinders, infrared adapters, and electro-optical and photographic adapters. All of the submarines in this study are equipped with two periscopes, search and attack. It is the author's opinion that every submarine is fitted with the above mentioned periscope augmentation gear, although the literature did not confirm this. The names of the periscope manufacturers are listed with their host submarines in Table 9-3.

8.3.3 Radar

Radar is used by submarines primarily for navigation during sea detail and other navigational situations, but could also be used in a combat role. Of particular interest is the Decca radar mounted on WALRUS. The Decca is popular on a number of commercial vessels, so the employment of it by WALRUS in a crowded shipping lane (and under limited visibility conditions) would not raise alarm. Available radar information is listed in Table 9-3.

COMMAND AND CONTROL	KILO	REF	WALRUS	REF	RUBIS	REF	BARBEL	REF	TYPE 2400	REF
					SUBMARINE NAME					
					SHIPS SENSORS					
PASSIVE SONAR	YES	(17)	SIASS	(22)	DSUV22	(17)	YES	(35)	T-2019	(7)
ACTIVE SONAR	YES	(17)	OCTOPUS		DUUA2B	(17)	BQS-4	(17)	T-2040	(7)
ARRAY SONAR	YES	(e)	T-2026	(7)	DUUX-5	(17)	?		TOWED	(7)
RADAR	SNOOP	(17)	DECCA		CALYPSO		YES	(35)	T 1007	(7)
ELECT SURVEILLNCE	YES	(e)	SIGNAAL		YES	(e)	YES	(35)	RACAL	(7)
PERISCOPES	YES	(e)	KOLLMORGAN		SOPELEM		2	(35)	BARR&STROU	
XBT	NO	(e)	NO	(e)	NO	(e)	YES	(e)	YES	(32)
INERTIAL GUIDANCE	SEMI	(e)	NO	(e)	NO	(e)	SEMI	(e)	SEMI	(e)
					COMMMUNICATION SYSTEMS					
U/W TELEPHONE	?		YES	(e)	TUUM		WQC-2		YES	(32)
HF RADIO	YES	(e)	YES	(e)	YES	(e)	YES	(e)	YES	(32)
VHF RADIO	YES	(e)	YES	(e)	YES	(e)	YES	(e)	YES	(32)
UHF RADIO	YES	(e)	NO	(e)	YES	(e)	YES	(e)	YES	(32)
VLF RADIO	YES	(e)	NO	(e)	YES	(e)	YES	(e)	(LF)	(32)
					AUTOMATED CONTROL STATIONS					
SHIP CONTROL									ONE-MA	(12)
MFGR:	SOME	(e)	SEWACO	(18)	YES	(e)	SOME	(e)		
MODEL:			VIII	(18)						
FIRE CONTROL									YES	(32)
MFGR:	YES	(e)	SIGNAAL		THOMSON-SINTRA		?		FERRANTI-GRESHAM	
MODEL:			GIPSY	(7)			MK-101		DCC	
PROPULSION										
MFGR:	SOME	(e)	YES	(e)	YES	(e)	SOME	(e)	YES	(32)
MODEL:										

Table 9-3: Command, Control, Communication, and Information systems. (Sheet one of two).

COMMAND AND CONTROL	TYPE 1700	REF	TYPE 2000	REF	SAURO	REF	VASTER-GOTL'D	REF	MIDGET 100	REF
SHIPS SENSORS										
PASSIVE SONAR	KAE	(7)	CSU 3-4		IPD 70/S		KAE CSU-83		YES	(7)
ACTIVE SONAR	KAE	(7)	CSU 3-4		IPD 70/S		KAE CSU-83		YES	(7)
ARRAY SONAR	DUUX-5	(7)	CSU 3-4		IPD 70/S		YES	(36)	NO	(e)
RADAR	SMA	(7)	YES		SMA 3RM20		THERMA	(36)	NO	(e)
ELECT SURVEILLNCE	NO	(7)	YES		YES	(12)	ARGO	(7)	NO	(e)
PERISCOPES	KOLLMORGAN		2		KOLLMORGAN		BARR&STROUD (TWO)	(33)		
XBT	YES	(e)	YES	(e)	NO	(e)	NO	(e)	NO	(e)
INERTIAL GUIDANCE	NO	(e)	NO	(e)	NO	(e)	SEMI	(36)	SEMI	(e)
COMMMUNICATION SYSTEMS										
UNDERWATER TELEPHONE			YES	(e)	YES	(12)	YES	(e)	NO	(e)
HF RADIO			YES	(e)	YES	(12)	YES	(36)	YES	(e)
VHF RADIO			YES	(e)	NO	(12)	NO	(e)	YES	(e)
UHF RADIO			YES	(e)	YES	(12)	YES	(36)	NO	(e)
VLF RADIO			NO	(e)	YES	(12)	NO	(e)	NO	(e)
AUTOMATED CONTROL STATIONS										
SHIP CONTROL										
MFGR:	SAGEM	(31)	YES	(e)	YES	(12)	SAAB	(19)	YES	(29)
MODEL:										
FIRE CONTROL										
MFGR:	SIGNAAL		YES	(e)	SEPA		DATA SAAB	(36)	YES	(29)
MODEL:	SINBADS				MK-3		NEDPS	(36)		
PROPULSION										
MFGR:	YES	(7)	YES	(e)	YES	(e)	YES	(e)	YES	(29)
MODEL:										

Table 9-3: Command, Control, Communication, and Information systems. (Sheet two of two).

8.3.4 Electronic Surveillance Measures

Electronic surveillance (ESM) is a more valuable combat tool than radar because the submarine does not reveal itself when using ESM. ESM is the passive sonar of the electronic information realm, and may be used to assist in the identification of a contact. The manufacturers of the submarine ESM gear are listed in Table 9-3.

8.3.5 External Communications

Table 9-3 lists the available information on communications systems.

The necessity of a submarine to be able to communicate with friendly operating forces is essential. Because of data links with aircraft and other surface units, surface ships generally have knowledge of a much greater area than submarines. The submarine must communicate with friendly forces in order to cooperate most effectively with friendly forces. The methods of communication available are various radio frequency bands, and underwater telephone. High frequency (HF) radio is generally used to communicate with shore stations by teletypewriter. Very high frequency (VHF) radio is used to communicate at distances just beyond the horizon. Ultra high frequency (UHF) is useful for line-of-sight communication, and as such has a shorter range but will allow the submarine to remain undetected to surface units beyond the horizon. Very low frequency (VLF) radio receivers were designed for use aboard strategic ballistic-missile submarines, but have been installed on some patrol submarines as well.

Underwater telephone may be used for two-way communication while the submarine is submerged, which is not possible with radio. Underwater telephone uses encoded sound pulses sent through the main active sonar array or through a separate dedicated transducer. It has limited range.

8.3.6 Automated Controls

Automated control systems have revolutionized the design of the submarine. By automating the propulsion and auxiliary plants, and integrating and computerizing the sensors and command centers, the required complement has been halved. A smaller complement frees up space and weight for other areas such as provisions, fuel, battery, or weapons reloads. The volume and weight cost of automating is less than the volume and weight saved due to the crew reduction it allows. The other costs of automating are a sharp increase in system complexity, with a multiplication of the probability of system failure, a decrease in systems availability, and an increase in preventative and corrective maintainance actions. Additionally, during casualty situations, when manual backup may become necessary, it is an advantage to have a high man-to-equipment ratio.

All of the submarines except BARBEL and possibly KILO use advanced automation technology and hardware. TYPE 1700, TYPE 2000, VASTERGOTLAND, and MIDGET 100 use it the most extensively, and with good results. Manufacturers of automation and control hardware are listed in Table 9-3.

8.4 Ship Support

The ship support functional group is concerned with the amount of space and weight needed to support the mobility, weapons, and C3I groups. It is made up of the habitability spaces, passageways, and provisions, and is directly proportional to the number of crewmembers. Depending upon one's viewpoint, the crew may or may not be included in the ship support functional group, but for this study, the crew itself is considered to be an integral and operational part of the other three functional groups. So ship support systems do not contribute directly to the performance of the submarine's mission, but are nonetheless essential to the proper functioning of the submarine as a whole.

Appendix K lists the most important physical and psychological factors affecting crew endurance. Submarine crews are an elite and dedicated group who are accustomed to the close quarters of life aboard a submarine, but each man has his own tolerance level for spartan conditions. Table 9-4

lists ship support and habitability parameters, many of which are only estimated from the reference pictures of the submarines. The most important parameter is the volume-per-man, given in cubic feet per man. WALRUS is by far the most voluminously-appointed vessel with 555 cubic feet/man, and MIDGET 100 is by far the least with one fifth of that value. The other boats are furnished with between approximately one-half to two-thirds the volume per man as WALRUS. An examination of the days of provision loadout for each vessel hints at the reasons for the great disparity in specific volumes - the mission duration of WALRUS is about five times that of MIDGET 100. Another explanation is that different cultures have different levels of personal privacy needs, and the respective shipbuilders have reflected that in thier designs.

Of particular note is that on BARBEL and SAURO, and MIDGET 100 as well, when loaded with combat swimmers, some berthing is located on the torpedo racks, whereas the other submarines have all be ,ng located in designated berthing compartments. Also, MIDGET 100 does not hav a mess room, although there is a space designated as the galley/scullery.

8.5 Acoustic Countermeasures

Stealth and undetectability are essential for effective combat actions particularly for diesel-electric submarines, which have a limited submerged range, and must be indiscrete while recharging batteries. Diesel-electric boats are considered quieter than nuclear boats when operating on battery, and there has been an intense effort by all

SHIP SUPPORT SYSTEMS	KILO	REF	WALRUS	REF	RUBIS	REF	BARBEL	REF	TYPE 2400	REF
TOTAL COMPLEMENT:	45	(17)	50	(24)	66	(8)	77	(17)	44	(32)
OFFICERS:	15	(e)	7	(17)	9	(8)	8	(17)	7	(32)
ENLISTED:	30	(e)	43	(17)	57	(8)	69	(17)	37	(32)
NR OF BERTHS	45	(e)	50	(e)	66	(10)	79	(35)	46	(32)
NR OF LOCKERS	45	(e)	50	(e)	66	(10)	19	(35)	44	(32)
NR OF MESS SEATS	25	(e)	40	(e)	32	(e)	26	(35)	26	(32)
FRESH WTR, Lton	4.5	(e)	10	(e)	13.2	(e)	53	(34)	21.9	(32)
EVAP PLNT, gal/day	450	(e)	1000	(e)	1320	(e)	924	(e)	840	(32)
WTR, gal/man-day	10	(e)	20	(e)	20	(e)	12	(e)	19.09	
NR OF COMMODES	3	(e)	5	(e)	4	(e)	4	(35)	3	(32)
AIR PURIFICATION	YES	(e)	YES	(23)	YES	(10)	YES	(35)	YES	(32)
P-WAY WIDTH, (in)	30	(e)	36	(e)	32	(e)	28	(35)	33.7	(12)
SHIP SUPPORT VOL:	14000	(e)	27752	(e)	15990	(e)	14562	(e)	11428	(e)
SS VOL/MAN:	311.1		555.0		242.2		189.1		259.7	
PROVISIONS, Days	45	(e)	70	(7)	60	(10)	60	(e)	49	(17)

SHIP SUPPORT SYSTEMS	TYPE 1700	REF	TYPE 2000	REF	SAURO	REF	VASTER-GOTL'D	REF	MIDGET 100	REF
TOTAL COMPLEMENT:	30	(8)	30	(5)	45	(12)	20	(36)	12	(33)
OFFICERS:	8	(e)	7	(e)	7	(e)	7	(e)	4	(e)
ENLISTED:	22	(e)	23	(e)	38	(e)	13	(e)	8	(e)
NR OF BERTHS	32	(8)	30	(e)	45	ON TORPS	20	(e)	8	(e)
NR OF LOCKERS	32	(e)	30	(e)	45	(e)	20	(e)	12	(e)
NR OF MESS SEATS	20	(e)	22	(e)	20	(e)	14	(e)	0	(e)
FRESH WTR, Lton	6	(e)	6	(e)	9	(12)	3.78	(e)	0.96	(e)
EVAP PLNT, gal/day	600	(e)	600	(e)	710	(12)	378	(e)	96	(e)
WTR, gal/man-day	20	(e)	20	(e)	15.77	(11)	18	(e)	8	(e)
NR OF COMMODES	3	(e)	4	(e)	2	(e)	2	(e)	2	(29)
AIR PURIFICATION	YES	(e)	YES	(e)	YES	(11)	YES	(36)	YES	(29)
P-WAY WIDTH, (in)	30	(e)	36	(e)	28	(e)	32	(e)	36	(e)
SHIP SUPPORT VOL:	10043		10000		9817		7564		1265	
SS VOL/MAN:	334.7		333.3		218.1		378.2		105.4	
PROVISIONS, Days	70	(21)	70	(e)	45	(21)	30	(e)	14	(33)

Table 9-4: Ship support systems parameters.

submarine manufacturers to reduce the sound emanation level as low as possible. with the desired goal of being only as noisy as the ambient ocean. This is actually a variable goal, since high sea-states are much noisier than low sea-states. and the silencing goal has certainly been met on a number of submarines for higher sea-states.

Some of the more prevalent and unclassified methods of submarine silencing are shown in Table 9-5. The use of propeller silencing, consisting of refinements in the hydrodynamic shape of the propeller, resilient mounts for machinery, and a low speed main shaft is common to all the boats. Only KILO and TYPE 2400 employ anechoic hull covering, and all boats except BARBEL have gearless main shaft drives. These parameters still only give qualitative indications of the silence of each submarine in operation, since the effectiveness of the silencing methods is likely to vary among the ships.

8.6 Survivability and Damage Control

A submarine is inherently a warship. Because of its limited volume and relatively high cost per ton, there are few commercial ventures which would choose a submarine over a surface displacement vessel. Being a warship, it must be expected that it shall be required to venture into harm's way. The importance of stealth, silencing, first detection, and first-strike capabilities have been discussed. The survivability shall now be discussed.

In the event that a submarine is hit. the strength and toughness of its hull. and its reserve bouyancy (ballast tanks) are the material-world determinants of its future. Information on hull strengths and geometry of construction are not available in the literature, but an estimate may be gleaned from knowledge of the immersion depth. Appendix L lists several factors impotant to submarine vulnerability and survivability.

ACOUSTIC COUNTERMEASURES	KILO	REF	WALRUS	REF	RUBIS	REF	BARBEL	REF	TYPE 2400	REF
RESILIENT MOUNTS	YES	(e)	YES	(17)	YES	(e)	YES	(e)	YES	(32)
ANECHOIC HULL COVR	YES	(e)	NO	(e)	NO	(e)	NO	(e)	YES	(32)
PROPELLER SILENCNG	YES	(e)	YES	(17)	YES	(e)	YES	(e)	YES	(32)
LOW SPEED SHAFT	YES	(e)	YES	(e)	YES	(e)	YES	(e)	YES	(e)
GEARLESS DRIVE	YES	(e)	YES	(e)	YES	(e)	NO	(17)	YES	(e)

	TYPE 1700	REF	TYPE 2000	REF	SAURO	REF	VASTER-GOTL'D	REF	MIDGET 100	REF
RESILIENT MOUNTS	YES	(e)	YES	(e)	YES	(12)	YES	(19)	YES	(29)
ANECHOIC HULL COVR	NO	(e)	NO	(e)	NO	(e)	NO	(e)	NO	(e)
PROPELLER SILENCNG	YES	(e)	YES	(e)	YES	(12)	YES	(19)	YES	(29)
LOW SPEED SHAFT	YES	(e)	YES	(e)	YES	(12)	YES	(19)	YES	(29)
GEARLESS DRIVE	YES	(e)	YES	(e)	YES	(12)	YES	(e)	YES	(29)

Table 9-5: Countermeasure outfit.

FLOODING PROTECTION	KILO	REF	WALRUS	REF	RUBIS	REF	BARBEL	REF	TYPE 2400	REF
NR OF WT COMPTMTS	4	(e)	3	(e)	3	(e)	3	(e)	3	(e)
VOLUME OF LARGEST WT SPACE, cuft	20000	(e)	26500		45930		18450		24720	
MBT VOLUME, cuft	24500		12250		9975		11340		8400	
MBT/COMPT RATIO:	1.225		0.462		0.217		0.614		0.339	

	TYPE 1700	REF	TYPE 2000	REF	SAURO	REF	VASTER-GOTL'D	REF	MIDGET 100	REF
NR OF WT COMPTMTS	3	(e)	3	(e)	3	(e)	2	(36)	1	(e)
VOLUME OF LARGEST WT SPACE, cuft	28923		26446		19300		19971		3370	
MBT VOLUME, cuft	7350		9310		6300		2450		420	
MBT/COMPT RATIO:	0.254		0.352		0.326		0.122		0.124	

Table 9-6: Compartment measurements germane to damaged survivability.

Table 9-6 details calculations of reserve bouyancy limits in a scenario involving flooding to the single largest compartment of the submarine. In the event of flooding, the main ballast tanks could be blown down, enabling the submarine to aviod sinking. The "MBT/COMPT" ratio is the fraction of the largest compartment volume which could be flooded before 90% of the reserve bouyancy would be expended in attempting to keep the submarine afloat. The favorite is KILO, which because of its greater degree of compartmentation and large ballast tanks, would be able to avoid sinking if damaged in only one compartment. This is not to say that KILO would remain mission-capable, or that subsequent shots would cause more extensive and irrecoverable damage, but all the other submarines are clearly one-shot platforms.

The KILO is the most capable submarine of those in this study to withstand severe damage. Its double-hull construction can withstand explosive warheads better than a single-hulled submarine of equal test depth rating, because the outer hull prevents the warhead from detonating as close to the pressure hull as it would have with a single-hull design. Reference (27) provides some insight to additional possible reasons for the use of double-hull designs by the U.S.S.R.:

> The pitiful peacetime safety record of Soviet submarines suggests serious design flaws, inattention to safety, lack of crew/shipyard maintainance of onboard equipment, and poor seamanship. Given the propensity of Soviet submarines to collide with submerged and surface objects, it was probably a wise decision to continue building more survivable doublehull submarines.

The bottom line of all this is that the capacity to withstand severe damage is certainly an asset, but the ability to avoid any damage at all, due to superior stealth, sensor range, weapon effectiveness, speed, and crew training state is a much greater asset.

8.7 Escape and Rescue

Table 9-7 lists the submarine escape and rescue facilities. Note that all of the submarines have been provided with at least one escape scuttle. The TYPE 1700 and TYPE 2000 are also equipped with escape pods of large enough capacity to hold the entire crew and provide them with four days sustainance.

CASUALTY PARAMETERS	KILO	REF	WALRUS	REF	RUBIS	REF	BARBEL	REF	TYPE 2400	REF
BATTERY SEGREGATION?	YES	(e)	NO	(e)	NO	(e)	NO	(e)	YES	(e)
DEGAUSSING	YES	(e)	YES	(e)	YES	(e)	YES	(e)	YES	(e)
ESCAPE AND RESCUE										
ESCAPE SCUTTLE?	YES	(17)	YES	(23)	YES	(e)	YES	(e)	YES	(32)
NUMBER OF SCUTTLES	2	(17)	2	(23)	2	(e)	2	(e)	2	(32)
ESCAPE POD ABOARD?	NO	(e)	NO	(e)	NO	(e)	NO	(e)	NO	(e)
POD CAPACITY	N/A	(e)	N/A	(e)	N/A	(e)	N/A	(e)	N/A	(e)
RESCUE BEACON?	YES	(e)	YES	(e)	YES	(e)	YES	(e)	YES	(e)

CASUALTY PARAMETERS	TYPE 1700	REF	TYPE 2000	REF	SAURO	REF	VASTER-GOTL'D	REF	MIDGET 100	REF
BATTERY SEGREGATION?	YES	(e)	YES	(e)	YES	(e)	NO	(e)	NO	(e)
DEGAUSSING	YES	(e)	YES	(e)	YES	(e)	ERICCS	(36)	YES	(e)
ESCAPE AND RESCUE										
ESCAPE SCUTTLE?	YES	(2)	YES	(e)	YES	(e)	YES	(36)	NO *	(e)
NUMBER OF SCUTTLES	1	(2)	1	(e)	1	(e)	1	(36)	N/A	(e)
ESCAPE POD ABOARD?	YES	(5)	YES	(5)	NO	(e)	NO	(e)	NO	(29)
POD CAPACITY	30	(5)	30	(5)	N/A	(e)	N/A	(e)	N/A	(29)
RESCUE BEACON?	YES	(e)	YES	(e)	YES	(e)	YES	(e)	NO	(29)

Table 9-7: Escape and Rescue capabilities.

Chapter 9

COMPARATIVE NAVAL ARCHITECHTURE

9.1 Specific Volumes

Table 10-1 lists the values of the weights of the functional groups divided by the volumes of the functional groups.

9.1.1 Mobility

For the mobility functional group, the weight/volume ratio seems to be related to the endurance range, with higher ratios occuring in submarines with shorter ranges. This is because bunker fuel is less dense than the propulsion machinery and battery, and the large fuel loads required for long ranges drop the average weight of the entire functional group.

9.1.2 Weapons Systems

The weight/volume ratios for the weapons systems are a function of how densely the space is packed with reload torpedoes. For MIDGET 100, the exceptionally high value is due to the exceptionally small portion of the pressure hull devoted to weapons, since the torpedoes are muzzle-loaded and there is no positive launching gear to take up space either. The ratios for BARBEL and SAURO are comparable to the ratios of the other subs because the volume over the torpedo racks used for berthing was charged to the ship support group.

COMPARATIVE ANALYSIS	KILO	WALRUS	RUBIS	BARBEL	TYPE 2400
Weight Fractions					
Wmob/Dsub	0.21882	0.28277	0.40189	0.21788	0.36161
Wwep/Dsub	0.02450	0.01731	0.02003	0.02425	0.02497
Wc3i/Dsub	0.02098	0.01795	0.01998	0.02122	0.03499
Wss/Dsub	0.03146	0.03503	0.04738	0.04433	0.04211
Specific Volumes					
Wmob/VOLm, lbs/cuft	47.5318	52.9003	50.0321	50.2536	52.4796
Wwep/VOLw, lbs/cuft	17.5638	11.6990	11.7750	19.6652	19.9672
Wc3i/VOLc, lbs,cuft	13.6764	19.0839	20.2974	18.7195	20.6143
Wss/VOLs, lbs/cuft	16.1123	7.91767	17.7243	17.9975	19.8121
Propulsion Plant Density					
Wmob/SHPi, lbs/HP	392.137	330.893	240.364	408.888	360.010
Ship Support Volume Per Crewmember					
VOLs/#C, cuft/man	311.111	555.04	242.272	189.116	259.727
Indiscretion Parameters					
Indiscretn Rate @ 6 Kts	0.080	0.067	N/A	0.074	0.126
Indiscretn Rate @10 Kts	0.232	0.199	N/A	0.227	0.360
Indiscretn Intrvl @ 6 Kts	32.7	34.1	N/A	46.6	36.7
Indiscretn Intrvl @10 Kts	10.7	11.0	N/A	14.7	11.8
Range Capabilities					
Bunker Fuel Range @ 6 Kts	14931	11227	1020	15735	8337
Provision Range @ 6 Kts	5760	10080	8640	8640	7056
Bunker Fuel Range @10 Kts	10713	7178	217	10993	5684
Provision Range @10 Kts	9600	16800	14400	14400	11760
Endurnce Range @ 6 Kts, Nm	5760	10080	8640	8640	7056
Endurnce Range @10 Kts, Nm	9600	7178	14400	9897	5221
Battery Range @ 6 Kts, Nm	196	204	42	280	220
Battery Range @10 Kts, Nm	107	110	22	147	118
Battery Range @18 Kts, Nm	29.4	29.9	5.1	40.8	32.4
Battery Range @25 Kts, Nm	N/A	N/A	1.8	N/A	N/A
Calculated Max Speed	18	20	25.1	17.8	20.5

WEAPONS DELIVERY COMPARISON	KILO	WALRUS	RUBIS	BARBEL	TYPE 2400
WEPS1: (Rb10)(#T)(#Wt)/1000	15.43	10.55	[illegible]	10.59	12.75
WEPS2: (R6)(#Wc)/1000	104	142	121	104	127
WEPS3: (R6)(#Wm)/1000	115	103	[illegible]	104	163
ESCAPE: (Id)(Vmax^2)	97200	[illegible]	[illegible]	38021	[illegible]
(Rb10)(#T)(#Wt)/Dsub	4.83	[illegible]	[illegible]	[illegible]	[illegible]
(R6)(#Wc)/Dsub	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
(R6)(#Wm)/Dsub	[illegible]	[illegible]	[illegible]	[illegible]	0.1

Table 10-1: Comparison of performance and design parameters.
Sheet one of [illegible].

COMPARATIVE ANALYSIS	TYPE 1700	TYPE 2000	SAURO	VASTER-GOTLAND	MIDGET 100
	Weight Fractions				
Wmob/Dsub	0.42035	0.39551	0.32099	0.36846	0.24896
Wwep/Dsub	0.01799	0.02512	0.04264	0.06862	0.11625
Wc3i/Dsub	0.01380	0.01712	0.03703	0.03617	0.04295
Wss/Dsub	0.02836	0.03253	0.04218	0.04333	0.06127
	Specific Volumes				
Wmob/VOLm, lbs/cuft	44.2359	46.9153	50.2038	53.8030	79.2533
Wwep/VOLw, lbs/cuft	16.6846	21.8591	18.4603	24.7112	87.4459
Wc3i/VOLc, lbs,cuft	15.1227	16.8685	18.8881	19.2311	17.6129
Wss/VOLs, lbs/cuft	14.8688	16.9795	15.9778	14.6297	14.7560
	Propulsion Plant Density				
Wmob/SHPi, lbs/HP	250.194	275.236	283.716	370.874	180.584
	Ship Support Volume Per Crewmember				
VOLs/#C, cuft/man	334.766	333.333	218.155	378.2	105.416
Indiscretn Rate @ 6 Kts	0.066	0.072	0.110	0.111	N/A
Indiscretn Rate @10 Kts	0.187	0.197	0.309	0.313	N/A
Indiscretn Intrvl @ 6 Kts	81.2	68.1	30.1	22.9	N/A
Indiscretn Intrvl @10 Kts	27.9	24.3	10.0	7.6	N/A
Bunker Fuel Range @ 6 Kts	15039	12651	9115	3231	1345
Provision Range @ 6 Kts	10080	12960	6480	4320	2016
Bunker Fuel Range @10 Kts	10736	9293	6891	1956	819
Provision Range @10 Kts	16800	21600	10800	7200	3360
Endurnce Range @ 6 Kts, Nm	10080	12651	6480	3231	1345
Endurnce Range @10 Kts, Nm	10736	9293	6891	1956	819
Battery Range @ 6 Kts, Nm	487	408	181	138	41
Battery Range @10 Kts, Nm	279	243	100	76	20
Battery Range @18 Kts, Nm	83.6	74.6	27.4	20.5	4.1
Battery Range @25 Kts, Nm	36.0	32.1	N/A	N/A	N/A
Calculated Max Speed	24.7	25	19.3	20	16.8

WEAPONS DELIVERY COMPARISON	TYPE 1700	TYPE 2000	SAURO	VASTER-GOTLAND	MIDGET 100
WEPS1: (Rb10)(#T)(#Wt)/1000	36.82	38.87	7.17	5.48	0.32
WEPS2: (R6)(#Wc)/1000	N/A	N/A	N/A	N/A	N/A
WEPS3: (R6)(#Wm)/1000	323	304	78	39	13
ESCAPE: (Id)(Vmax^2)	183027	203125	111747	120000	56448
(Rb10)(#T)(#Wt)/Dsub	15.67	16.68	4.32	4.81	2.35
(R6)(#Wc)/Dsub	N/A	N/A	N/A	N/A	N/A
(R6)(#Wm)/Dsub	0.1	0.1	0.0	0.0	0.1

Table 10-1: Comparison of performance and design parameters. (Sheet two of two).

9.1.3 Command, Control, Communications, and Information

All the ratios are about the same except for KILO, which is presumably lower due to the extra volume taken up by the vacuum-tubes and the additional HVAC ducting needed to maintain the temperature.

9.1.4 Ship Support

All of the values are about the same except for WALRUS, which has an exceptionally large ship support volume. WALRUS apparently has been designed with extra volume to allow greater crew comfort during the exceptionally long (70+ days) missions of which this vessel is capable. The empirical formula for ship support weight developed in Appendix I is a stronger function of complement than of vessel size.

9.2 Mobility Weight/Installed Power

An economy of scale is evident in the ratio of mobility weight to installed shaft horsepower, with lower ratios occuring for higher SHPI, on vessels such as RUBIS, TYPE 1700, and TYPE 2000. The low value for SAURO is due to its densely-packed engine room, a design trait for which Fincantieri is well known.

9.3 Overall Endurance Ranges at Six and Ten Knots

Ten knots is a reasonable speed for a diesel-electric submarine in transit to or from the operating area. Six knots is a reasonable speed for patrolling a choke-point operating area. Overall endurance range at ten knots is the fuel endurance range for the subject submarines, and the overall endurance range at six knots is in general determined by the provision endurance. Figure 10-1 shows a comparison of these ranges. The long range of the nuclear-powered RUBIS at ten knots is of note, as is the short range of

MIDGET 100 at both speeds. MIDGET 100 may be towed to the operating area, but is probably best at missions of shorter duration, as is apparently also the case for TYPE 2400 and VASTERGOTLAND. VASTERGOTLAND was most likely designed to patrol the coast of Sweden looking for KILO and other Soviet submarines, which have an affinity for the fiords. The other boats were probably designed for, and are capable of, long range solo transits to and from a remote location, and with enough fuel and provisions remaining to spend a healthy amount of time at the operating area.

9.4 Battery Endurance Range

Figure 10-2 shows a comparison of the battery ranges of each submarine at speeds of six, ten, eighteen, and twenty-five knots. TYPE 1700 and TYPE 2000 are the best in this area. They are also the only submarines to have appreciable battery range at twenty-five knots, although RUBIS would be expected to go nuclear its limited battery energy was exhausted and it still needed to make that speed. Battery endurance range is of great combat significance, because the submarine is much less detectable when on battery than when snorkeling.

9.5 Indiscretion Rate and Interval

Once at the opearating area, the diesel-electric submarine will need to recharge its batteries from time to time. If operating in a war zone, low indiscretion rate and long indiscretion interval may be crucial to the submarine's combat effectiveness. With a long indiscretion interval, the submarine skipper has the flexibility to choose the best time to recharge batteries. Notification of that time could even come from a shore station or other friendly units, based upon satellite information or other sensor data.

Figures 10-3 and 10-4 show a comparison of the indiscretion rates and intervals at

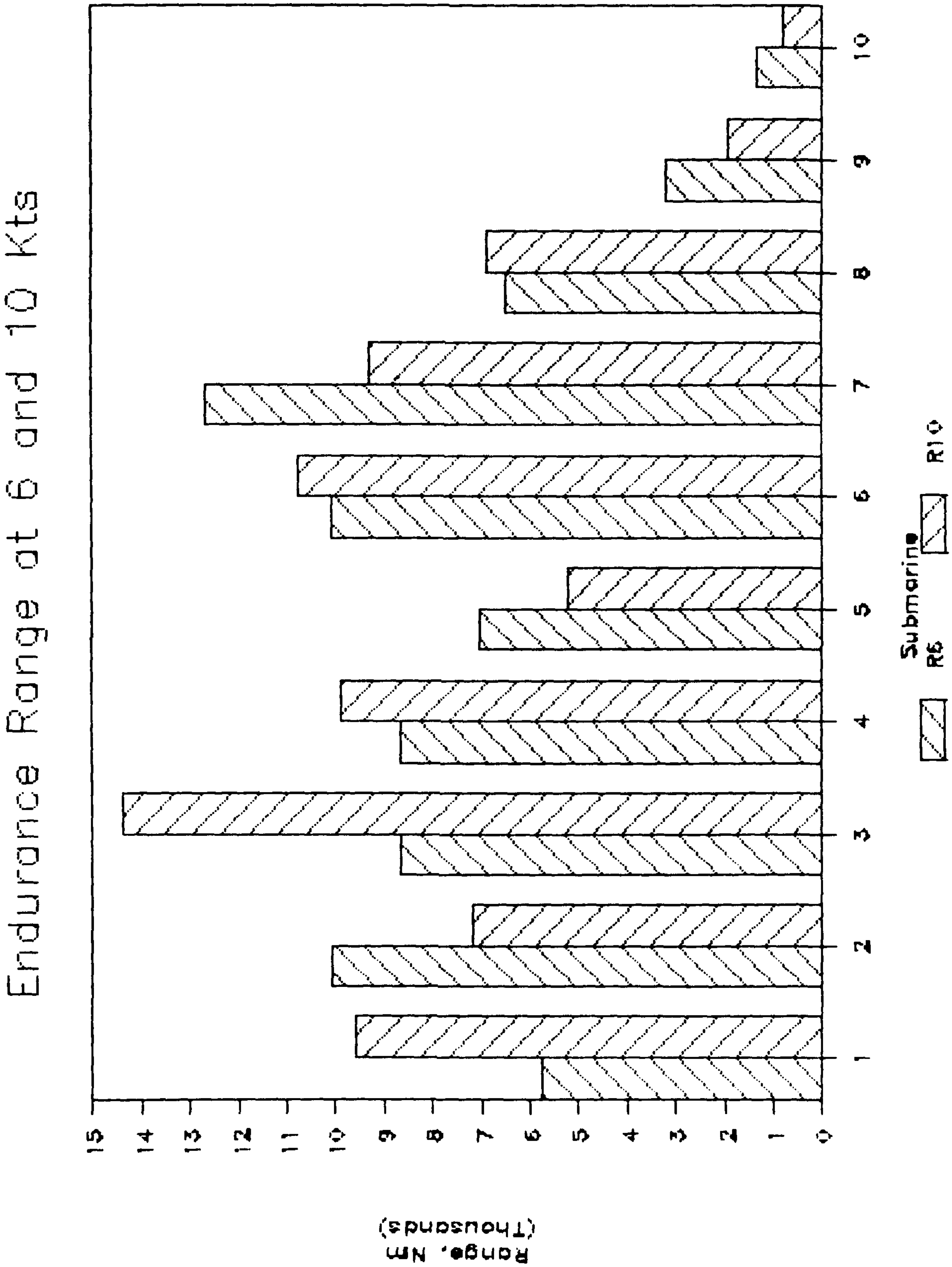


Figure 10-1: Comparison of Overall Endurance Ranges at Six and Ten Knots.

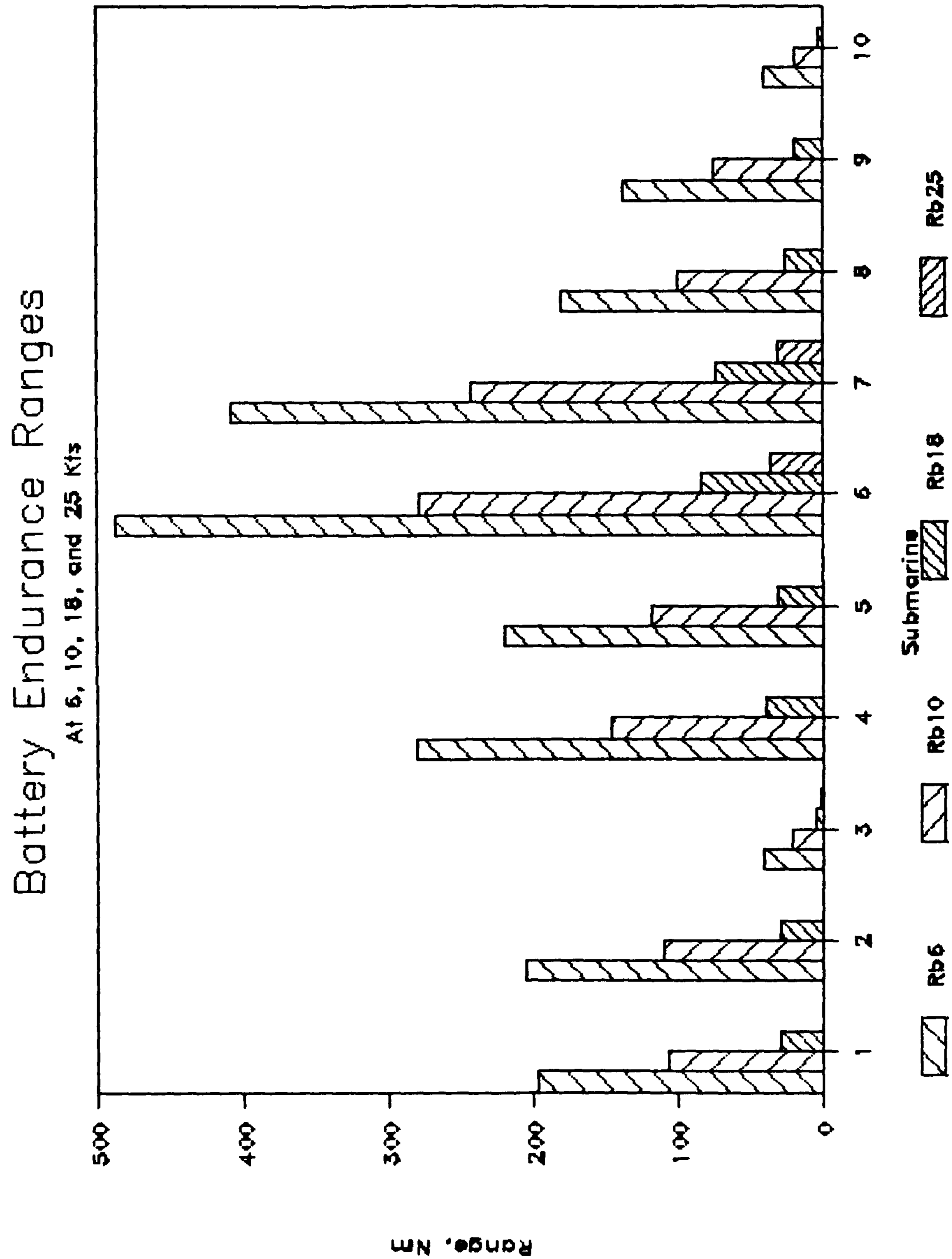


Figure 10-2: <u>Comparison of Battery Endurance Range at Six and Ten Knots.</u>

speeds of six and ten knots. Of immediate note is the fact that RUBIS and MIDGET 100 have zero indiscretion rates and indefinitly long indiscretion intervals, since neither of them needs to snorkel in order to recharge batteries. TYPE 1700 and TYPE 2000 have the next best ratings, due to their very large batteries and large diesel alternator sets.

9.6 Escape Capability

Figure 10-5

shows each submarine's rating on an arbitrary parameter designed to evaluate escape capability once detected. The parameter places a premium upon top speed due to its importance in outrunning a torpedo. The parameter is the product of the immersion depth and the square of the top submerged speed. Immersion depth is important because internal combustion propelled torpedoes have decreased range with increased depth. The high scorers are RUBIS, TYPE 1700, and TYPE 2000. The low ratings for BARBEL, TYPE 2400, and MIDGET 100 are a result of their poor immersion depth and lower top speed.

9.7 Weapons Delivery Capabilities and Platform Efficiencies

9.7.1 Torpedoes

The ability to deliver ordnance on target is essential for combat effectiveness. For a measure of overall torpedo delivery effectiveness, an arbitrary parameter is the product of battery endurance range at ten knots, number of torpedo tubes, and number of torpedoes carried. This product is then divided by 1000 for scaling. An arbitrary parameter for the platform efficiency of torpedo delivery would be the same product divided by submerged displacement. Figure 10-6 compares the calculated values of these parameters.

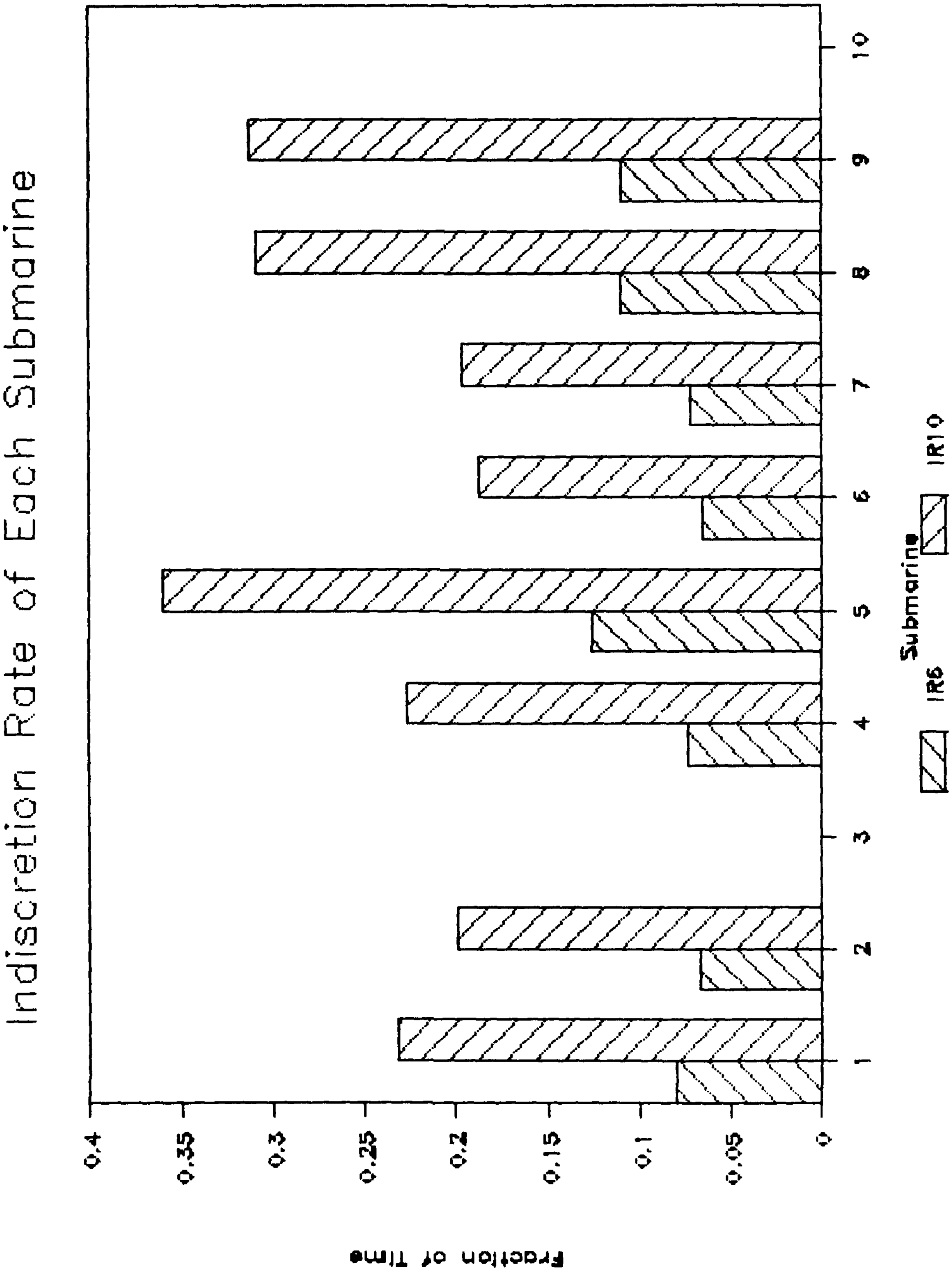


Figure 10-3: Comparison of Indiscretion Rates at Six and Ten Knots.

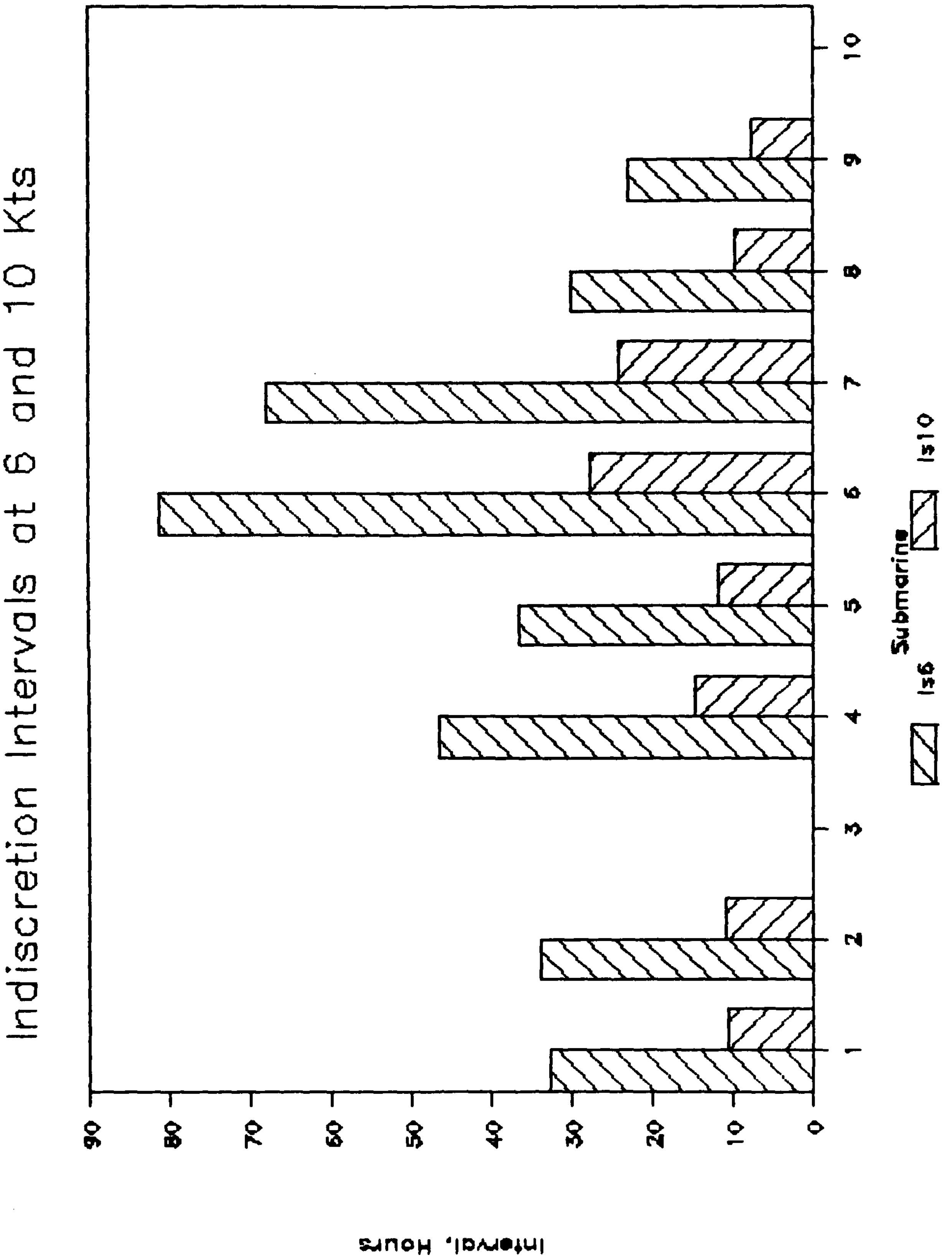


Figure 10-4: Comparison of Indiscretion Intervals at Six and Ten Knots.

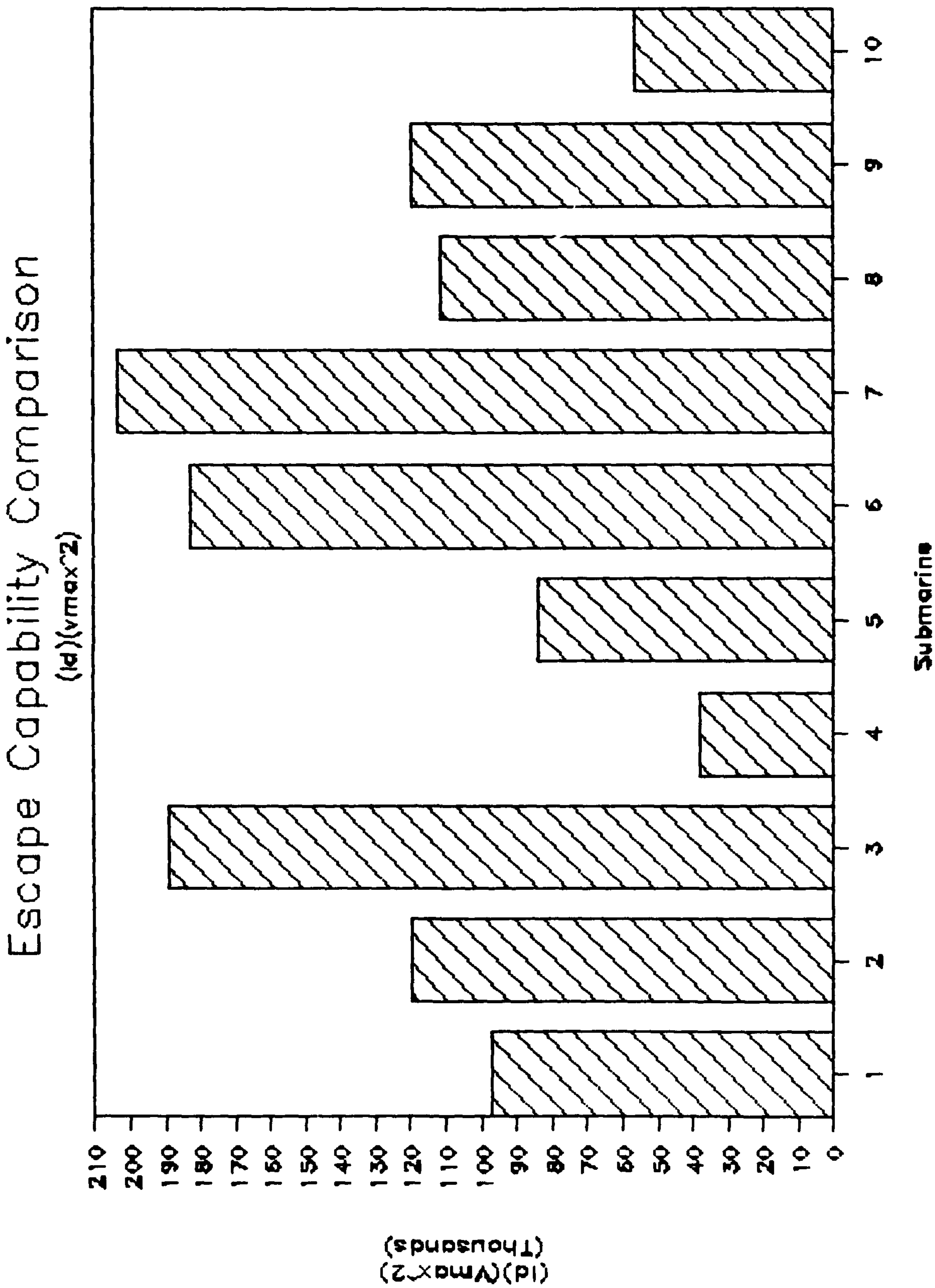


Figure 10-5: Comparison of Escape Capability Parameter.

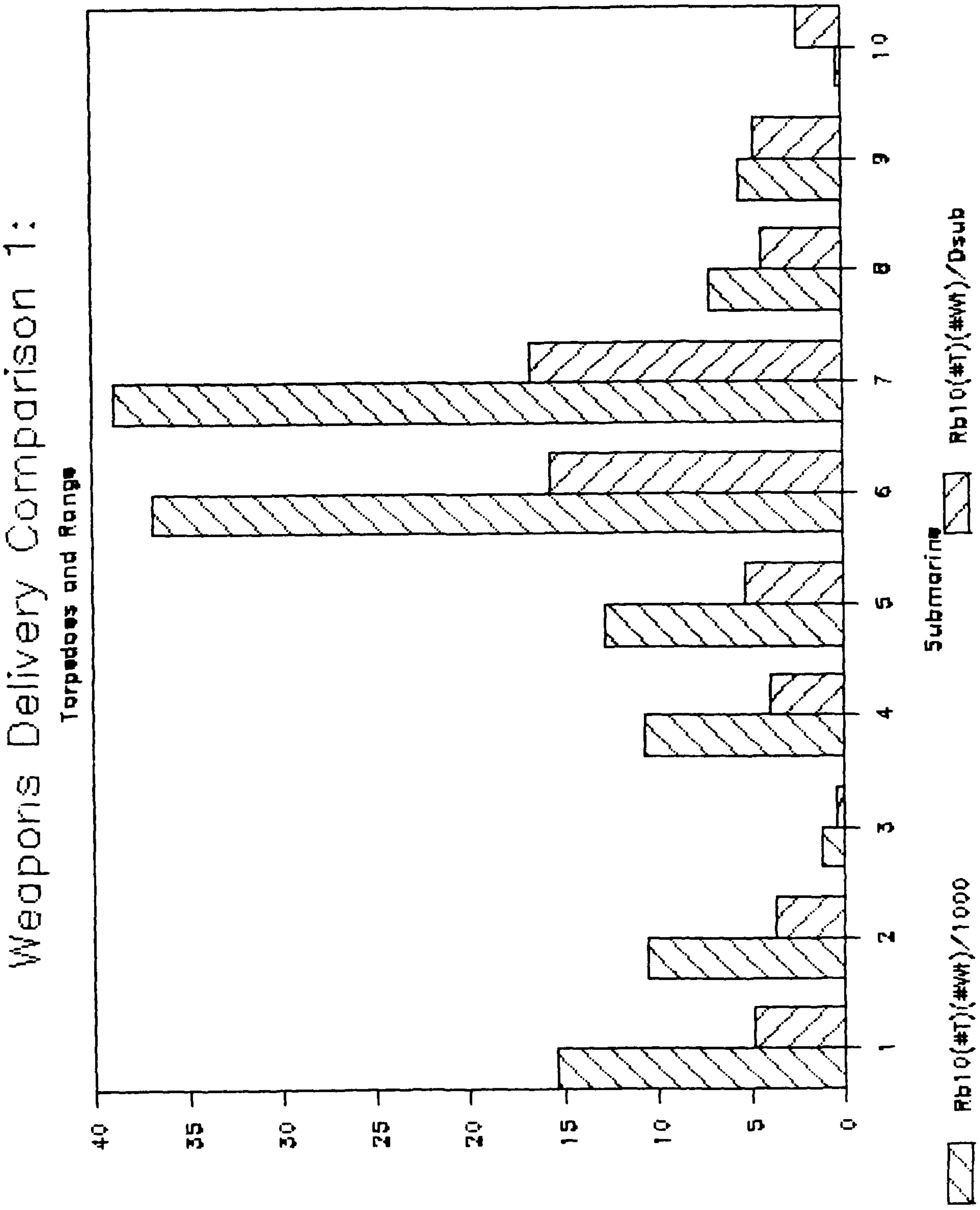


Figure 10-6: Weapons Delivery Parameter: Torpedoes and Battery Range at Ten Knots.

The high values for TYPE 1700 and TYPE 2000 are again a result of the outstanding battery endurance range of those vessels, combined with their large torpedo loadout. The low score for RUBIS is not truly repesentative of that submarine's combat effectiveness, since reactor range at ten knots is much greater, but is included for comparison. The platform efficiencies of KILO, WALRUS, BARBEL, TYPE 2400, SAURO, and VASTERGOTLAND are all inthe same range, and the platform efficiency of MIDGET 100 is not much below that.

9.7.2 Cruise Missiles

For a measure of overall cruise missile delivery effectiveness, an arbitrarty parameter is the product of overall endurance range at six knots and the number of cruise missiles carried. This product is then divided by 1000 for scaling. An arbitrary parameter for the platform efficiency of cruise missile delivery would be the same product divided by submerged displacement. Figure 10-7 compares the calculated values of these parameters. The overall endurance range at six knots is used because the stand-off launch mode of the cruise missile does not require lengthy periods on battery as torpedo attacks do, and instead, the emphasis should be placed upon endurance on station.

WALRUS stands out as the leader in this area because of its high weapons loadout capacity and excellent slow-speed endurance range due to its high provision loadout. TYPE 1700, TYPE 2000, SAURO, VASTERGOTLAND, and MIDGET 100 fail to score in this area due to the inability of their torpedo tubes to launch cruise missiles. KILO, RUBIS, BARBEL, and TYPE 2400 are all approximately equal in both overall capability and platform efficiency.

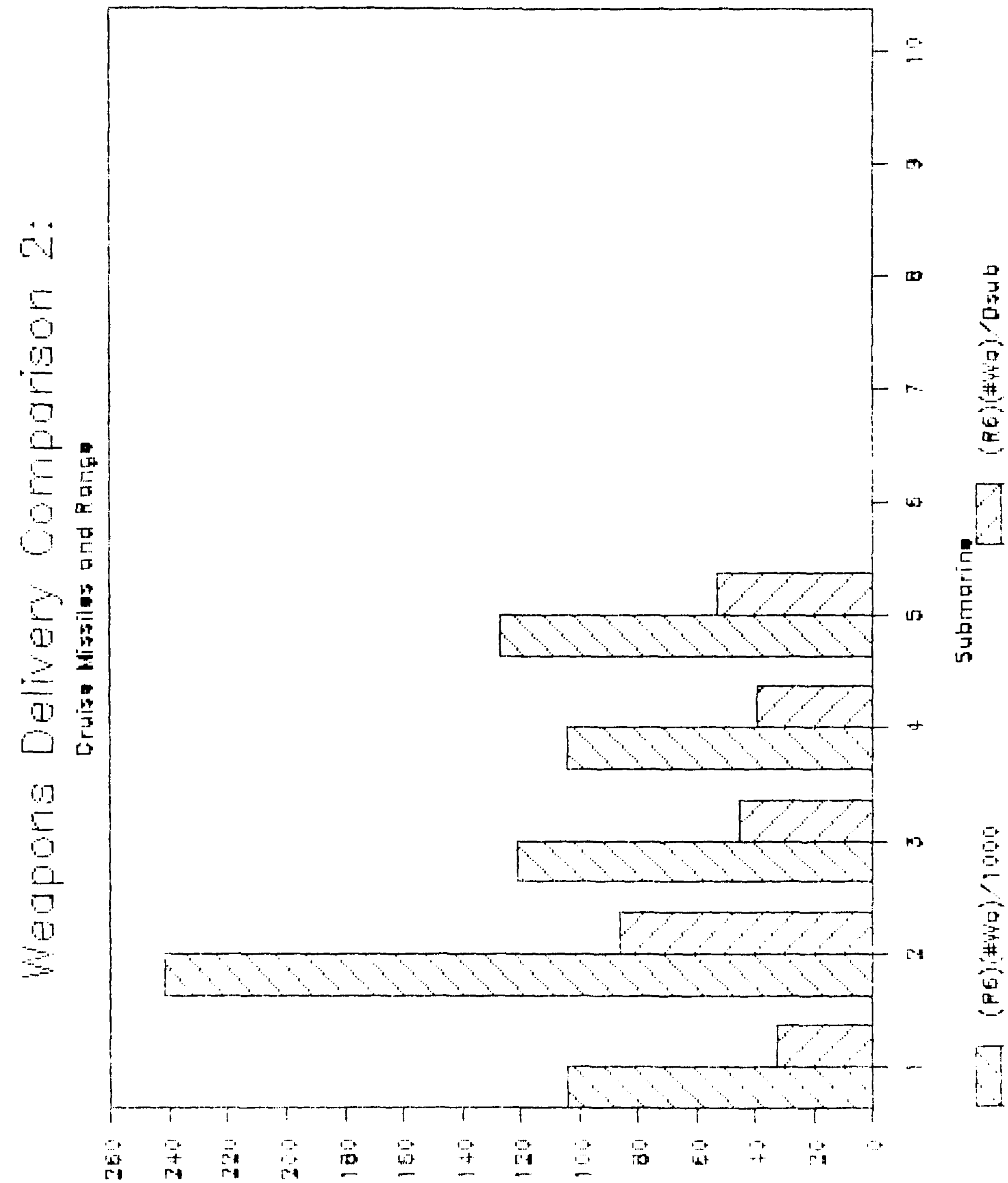


Figure 10-7: Weapons Delivery Parameter: Cruise Missiles and Fuel Endurance Range at Six Knots.

9.7.3 Mines

For a measure of overall mine delivery effectiveness, an arbitrarty parameter is the product of overall endurance range at six knots and the number of mines carried. This product is then divided by 1000 for scaling. An arbitrary parameter for the platform efficiency of mine delivery would be the same product divided by submerged displacement. Figure 10-8 compares the calculated values of these parameters. The overall endurance range at six knots is used to represent the degree of flexibility the submarine would have in remaining on station to pick the best time to place the mines. Actual placement of the mines would usually be conducted on battery.

WALRUS again leads the pack in this area due to its high loadout of provisions for long endurance and mines for combat effectiveness. TYPE 1700 and TYPE 2000 achieve good scores as well, and have about the same platform efficiency as WALRUS. MIDGET 100 is next for platform efficiency, and might be even higher if the analysis were to include the contributions of the auxiliary mine pods which may be loaded externally. The remaining boats are reasonably effective minelaying vehicles.

9.8 Conclusions

This study places a great deal of importance on speed and endurance range. The author states that these are essential attributes for combat effectiveness, and are suitable indices of comparison in lieu of more subtle, or unavailable, parameters such as sensor ranges, sound emanation profiles, equipment failure rates, or casualty control needs.

The main conclusion to be drawn is that automation of systems will allow a reduction of crew size, which then permits a larger battery and greater provision, fuel, and weapons loadouts. This will lead to greater combat effectiveness due to increased range, attack flexibility, speed, and weapons delivery potential.

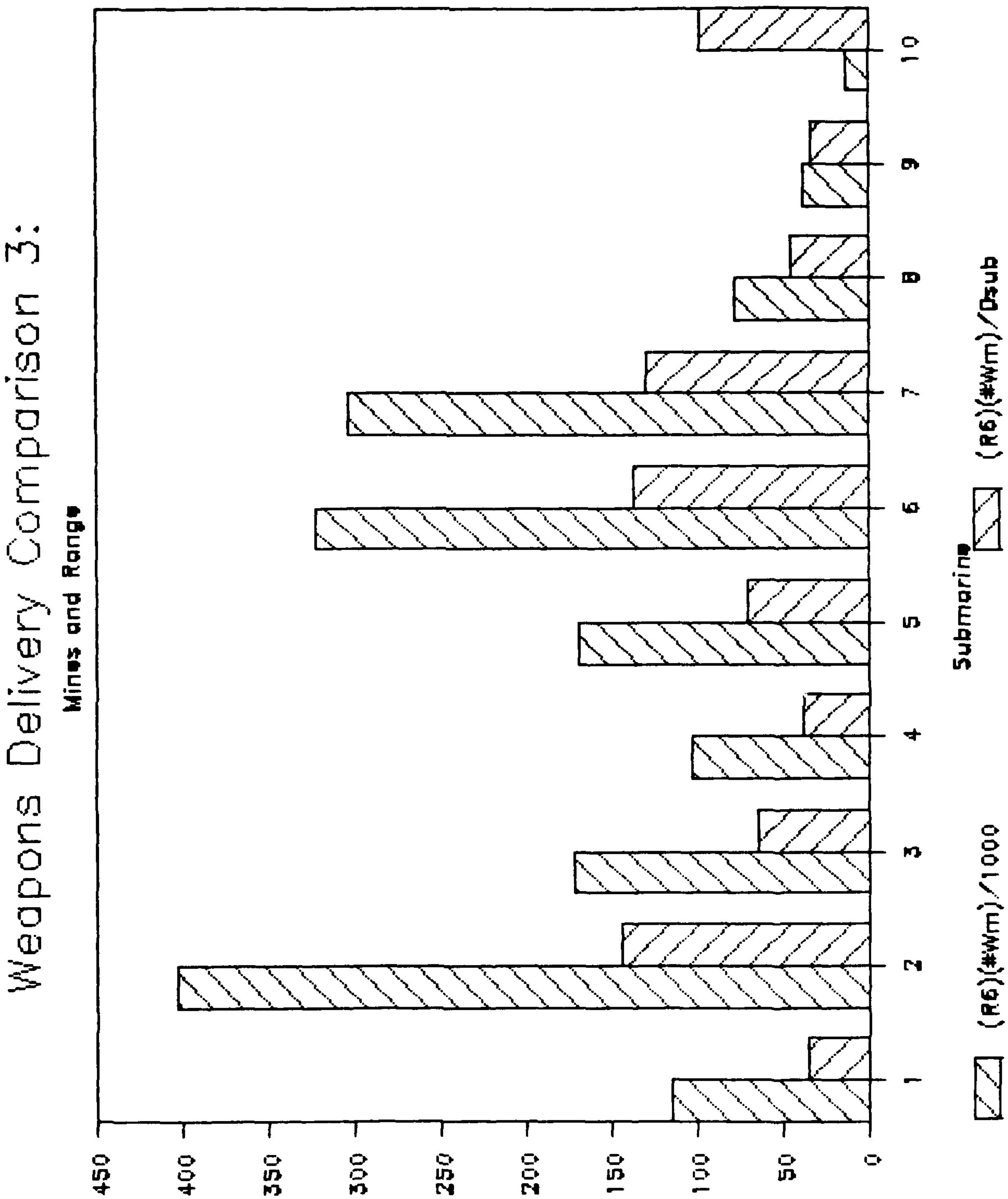


Figure 10-8: Weapons Delivery Parameter: Mines and Fuel Endurance at Six Knots.

Chapter 10

AREAS FOR FURTHER STUDY

The following areas would increase the depth of this study and enable a more comprehensive comparison between the subject submarines.

10.1 Maneuvering Characteristics

The maneuvering capabilities of each submarine could be modeled and the results used to develop tactical engagement and attack parameters and techniques.

10.2 Weight Distribution

The determination of weights and weight distributions of each system and functional group needs to be accomplished. The weights calculated in this study are all based upon the same empirical formulas, so the notion of comparing one submarine's weight groupings to another's is impossible. It may be impossible to publish a study of this detail, since the actual values of submarine weight groups are often proprietary data, if not classified.

10.3 Specific Fuel Consumption Increase at Snorkel

Many state-of-the-art diesel engines have SFC's in the low 0.30's (lb/HP-Hr) when run on the test bed. The additional fuel consumption increase due to the flow restrictions in the intake and exhaust ducts could be accomplished. The result would improve the accuracy of the calculated endurance range. Additionally, a relation should be possible between the increase in SFC due to the length of the intake and exhaust trunks, and the additional horsepower needed to operate close to the surface, so that an optimum sail height for anticipated snorkeling speed could be found.

10.4 Hull Strength Estimation

A model of each submarine's pressure hull could be developed, and analyzed for actual crush-depth estimate. Several of the submarines have the same published minimum (normal) operating depth, how much safety factor (or military discretion) has been employed in each? This model also probably could not be accomplished with much accuracy with only open-literature sources.

10.5 Weapons and Sensors Capabilities

The focus of this study was comparative design of the marine engineering aspects of the submarines. The weapons systems capabilities and the sensor ranges of each submarine could be researched or estimated, and a more thorough evaluation of the combat effectiveness of each submarine could be accomplished.

Chapter 11

REFERENCES

1. "Anaerobic Diesel-Powered Midget Submarine With Extended Non-Snorkel Submerged Range", Maritime Defense, Volume 11, Number 4. April, 1986.

2. "Canadian Submarine Acquisition Program (CASAP)", Wings Magazine. Issue devoted to Canada's Navy. Fall 1987.

3. Carmichael, A. Douglas. "Notes from MIT Course 13.21: Naval Ship Power and Propulsion". Fall Term, 1987.

4. Coeshall, Bob. "Submarine Manoevering Control, Requirements of Modern Platform Control". Maritime Defense, Volume 8, Number 4. April, 1983.

5. "Conventional Submarines - A Further Review". The Naval Architect. May, 1983.

6. "Diesel-Electric Submarines". Maritime Defense. Volume 10, Number 1. January, 1985.

7. "Diesel-Electric Submarines and Their Equipment". International Defense Review. Supplement V/1986. 1986.

8. "Diesel-Electric Submarines - Thyssen Nordseewerke Launches First TR 1700 and Wins Norwegian Order". Maritime Defense. Volume 7, Number 10. October, 1982.

9. Direction Des Constructions Navales. "SSN, 'RUBIS' CLASS, 'AMETHYSTE' BATCH", Direction Des Constructions Navales. France, 1986. Manufacturer's Brochure.

10. Direction Des Constructions Navales. "SSN, 'RUBIS' CLASS". Direction Des Constructions Navales, France. September 1984. (Industrie Catalogues (1) 737.13.13).

11. Fairplay Marine Diesel Engine Directory. Fairplay International Records and Statistics. London, United Kingdom. 1980.

12. Fincantieri, Cantieri Navali Italiani S.p.A. "SAURO-Class Submarine". Fincantieri. Cantieri Navali Italiani S.p.A., Italy, (undated). (Manufacturer's Brochure).

13. "HMS UPHOLDER, Type 2400", Navy International. Volume 92, Number 7. July/August 1987.

14. Heggstad, Kare M. "Submarine Hulls of Titanium, the Soviet 'Alfa' Class - Fact or Fiction". Maritime Defense. Volume 8, Number 4. April, 1983.

15. "The IKL Submarine Escape Sphere". Maritime Defense. Volume 11, Number 3. March 1986.

16. Jackson, Harry, P.E., CAPT USN (Ret). "Submarine Design". Notes from Charles Stark Draper/MIT Professional Summer Course. 1982.

17. Jane's Fighting Ships 1987-1988. Janes Publishing Company, Ltd. London. England. 1987.

18. Jordan, John. "Netherlands' WALRUS Submarine Takes to the Water". Jane's Defense Weekly. Volume 4, Number 19. November 9, 1985.

19. "Kockums Concentrates on Submarines". The Naval Architect. March, 1986.

20. Linden, David, Editor-in-Chief. "Handbook of Batteries and Fuel Cells". Mcgraw-Hill Book Company. New York, 1984.

21. Lotus 1-2-3, Release 2. Lotus Developement Corporation. Cambridge, Mass.

22. NAVY International. Volume 89 . Number 12. December, 1984.

23. Polmar, Norman. "Guide to the Soviet Navy", 3rd Edition. U.S. Naval Institute Press. Annapolis, MD, 1983.

24. RDM Naval Engineering. "Naval Engineering", RDM Naval Engineering. Rotterdam, The Netherlands, (undated). Manufacturer's Brochure.

25. "Soviet 'AKULA" Submarine in Close-Up". JANES Defense Weekly. Vol 7, Issue 7. Feb 21, 1987.

26. "Soviet KILO Class Submarines for Poland and India". Military Technology. Vol 10. Number 8. Aug 10, 1987.

27. "Soviet Sub Design Philosophy." Proceedings. U.S. Naval Institute. Annapolis, MD. Volume 113, Number 10. Oct 1987.

28. Strang, Gilbert. "Introduction to Applied Mathematics". Wellesley-Cambridge Press. Cambridge, Mass. 1986.

29. Sub Sea Oil Services. "GST Midget 100 MK1 OGP-27". Sub Sea Oil services of Micoperi, S.p.A. Manufacturer's Brochure. (undated).

30. "The Swedish 'VASTERGOTLAND'-Class Submarine". Maritime Defense. Volume 8, Number 4. April, 1983.

31. "Thyssen Nordseewerke and the TR-1700". Maritime Defense. Volume 8. Number 4. April 1983.

32. "Type 2400 Patrol Class Submarine". Vickers Shipbuilding and Engineering, Ltd. England, July, 1981. Manufacturer's Brochure.

33. U.S. Navy. "A 100-Ton Submarine Design From Italy". Office of Naval Research. Volume 20-86. 18 March, 1986.

34. U.S. Navy. "Final Weight Report for SS-580". U.S.N. Bureau of Ships. 27 August, 1959.

35. U.S. Navy. "USS BARBEL Arrangement Drawings". BuShips Dwg SS580-845-1702763. U.S.N. Bureau of Ships. 1959.

36. "Vastergotland A17 Type Submarines". International Forum for Maritime Power. Naval Forces Issue. Number III. 1983.

37. Varta Corporation. "Quarter of a Century of Modern Submarine Battery Technology". Maritime Defense. Volume 11, Number 3. March, 1986.

APPENDIX A: GEOMETRY CALCULATIONS FOR ESTIMATING SUBMARINE COMPARTMENT VOLUMES

In order to determine the internal volumes of the submarines to the greatest degree possible, generic submarine hull components were modeled on a computer spreadsheet.

Since the pressure hull is composed primarily of cylynder sections, truncated cones, and hemispheres, the computer modeling is as easy as summing the volumes of the component sections. The formulas used to model these compont sections are as shown below. The formulas were input to a computer spreadsheet, Reference (21), to facilitate computations. This worksheet, "SECTOR3.WK1" is included on the following page.

CYLYNDER: $\text{Vol} = 2*PI*R*L$ EQN A-1

CYLYNDER SECTION: $\text{Vol} = \frac{L*R^2}{2}*(ACOS\ \frac{R-z}{R}) - (\frac{L*R*(R-z)}{2})$, EQN A-2

TRUNCATED CONE: $\text{Vol} = (PI/3) * L * [R^2 + R*r + r^2]$, EQN A-3

TRUNCATED CONE SECTION:

$\text{Vol} \approx \sum_{i=1}^{n} \frac{iL*R^2}{2}*(ACOS \frac{R-iz}{R}) - (\frac{L*R*(R-iz)}{2})$, EQN A-4

```
"SECTOR3.WK1"        (MAY BE USED FOR SUBMARINE VOLUME CALCULATIONS)
                     (ASSUMES THREE-DECK ARRANGEMENT SCHEME)
                    CALCULATES COMPARTMENT VOLUMES.
SECTOR AREA = R^2(ACOS((R-H)/R)-(R-H)(SQRT(R^2-(R-H)^2)
========================================================================
CIRCLE RADIUS: (R)     13.8  (input) CIRCLE RADIUS: (R)     13.8  (input)
TOPSECTOR HEIGHT:     20.48  (input) BOTMSECTOR HEIGHT:    2.936  (input)
      (R-H):          -6.68                (R-H):         10.864
------------------------------------------------------------------------
TOPSECTOR AREA:    476.0334          BOTMSECTOR AREA:  34.09241

                  MID SECTOR AREA:        88.159004426
------------------------------------------------------------------------
TOPCOMPT LENGTH:     23.487  (input) BOTMCOMPT LENGTH:     21.31  (input)
TOPCOMPT VOLUME:   11180.59          BOTMCOMPT VOLUME: 726.5093
                                                       18.47409
MIDCOMPT LENGTH:         46  (input) CYLYNDER LENGTH:        44
MIDCOMPT VOLUME:   4055.314          CYLYNDER VOLUME:  26324.53
====================================CYLYNDER DISPL:   752.1295 =========
------------------------------------------------------------------------
VOLUME OF A TRUNCATED RIGHT-ANGLED CONE:
DIMENSIONS:
SMALL END RADIUS:     r =      10.996
LARGE END RADIUS:     R =      13.772
LENGTH:               L =        7.79

VOLUME:               V =    3768.981      (PI*L/3)*(R^2+r^2+rR)
------------------------------------------------------------------------
VOLUME OF A CONE: (LARGE END AND LENGTH ONLY)
VOLUME:               V =    1547.248
------------------------------------------------------------------------
```

APPENDIX B: NUMERICAL APPROXIMATION OF SUBMARINE WETTED SURFACE AREA

The calculation of the wetted surface area of the bare hull, sail, and appendages is crucial to being able to solve for the effective horsepower required at various speeds. An accurate calculation of the wetted surface is difficult because of the generally non-isometric drawings of the submarines in the literature. Accuracy may be improved by using numerical modeling methods. Such a method is used in the interpolating program "SPLIN500.WK1" on the following pages which uses cubic spline matrices to approximate the surface of a body of revolution, then numerically evaluates the surface area from the interpolating polynomials. The cubic spline technique is from Reference (28), and the program is implemented on Lotus 1-2-3 (Rel 2), of Reference (21). The inputs are the measured radii at evenly-spaced stations, and the overall length of the submarine. the outputs are a set of station slopes, interpolating third-order polynomials, and the surface area of each section and the entire submarine as well. Table B-1 method should be used with caution, because although the cubic-spline method guarantees that the cubic interpolating polynomials, and their first and second derivatives, will be continuous over the body, it cannot guarantee that the surface so generated will accurately represent the surface from which the radii were extracted.

Another numerical modeling scheme is presented as "HERMFAST.WK1". This model uses Hermite polynomials, also from Reference (28), to determine the cubic interpolating functions. The inputs to this model are both the radii and slopes at sequential stations, and with the added information of the slopes, this model is able to calculate the surface area to as accuarate as the input data from the reference drawing will allow. Stations need not be evenly spaced either. As few as two station data inputs are possible for the model to work, but accuracy is improved with more stations. with a maximum of eleven input stations currently programmed. The outputs are interpolating polynomials, the section areas, and the wetted surface of the entire bare hull. An run of HERMFAST is presented here, with the input values for TYPE 2400 input as an example.

The wetted surface areas calculated by these models are accuate for bodies of revolution, so corrections must be made to account for the deck, skeg, tumblehome, and any other protrusions.

The surface areas of the sail and the appendages are measured from the available photographs or diagrams in the literature as best as possible.

"SPLIN500.WK1" USED TO CALCULATE SURFACE AREA OF A BODY OF REVOLUTIO

The inputs are the station radii. The outputs are cubic interpolati polynomials which form a curve which has continuous first and second derivatives. CAUTION: The resultant body may not adequately model t geometry of the actual body, since station slopes are not specified!

(USES CUBIC SPLINE MATRICES, FROM STRANG, pp 177-180.)

PROCEDURE:
(1) INPUT ACTUAL LENGTH AND RADII AT THE ELEVEN (EQUALLY-SPACED) STA
(2) HIT [F9] TO CALCULATE.
(3) MULTIPLY THE MATRIX AT K32 BY THE MATRIX AT W32, RESULT TO Y32.
(4) HIT [F9] AGAIN TO GET SLOPES, INTERPOLATING COEFFICIENTS, AND AR

===

INPUTS:

ACTUAL LENGTH: 10 | NORMALIZED LENGTH: 10

OUTPUTS:

STATION SPACING: --> 1 (lamda)

STATION:	ACTUAL RADIUS:	NORMALIZED RADIUS:	SLOPE AT STATION:		SURFACE AREA
0	0	0	S0:	-4.1E-18	---------
1	0	0	S1:	8.2E-18	3.2E-18
2	0	0	S2:	-1.0E-16	5.8E-17
3	0	0	S3:	-1.1E-16	4.1E-17
4	1	1	S4:	3	3.563441
5	4	4	S5:	1.0E-17	51.21251
6	1	1	S6:	-3	51.21251
7	0	0	S7:	1.2E-16	3.563441
8	0	0	S8:	6.1E-17	4.2E-17
9	0	0	S9:	-1.9E-17	4.1E-17
10	0	0	S10:	9.3E-18	1.5E-17

OUTPUT: COEFF. OF (NORMALIZED) INTERPOLATING POLYNOMIALS, U(x).

	a	b	c	d
0 to 1:	4.1E-18	0	-4.1E-18	0
1 to 2:	-9.4E-17	3.7E-16	-4.5E-16	1.7E-16
2 to 3:	1.6E-15	1.6E-15	-3.9E-15	3.1E-15
3 to 4:	1	-9	27	-27
4 to 5:	-3	39	-165	229
5 to 6:	3	-51	285	-521
6 to 7:	-1	21	-147	343
7 to 8:	1.8E-16	-4.0E-15	3.0E-14	-7.6E-14
8 to 9:	4.2E-17	-1.1E-15	9.8E-15	-2.9E-14
9 - 10:	-9.3E-18	2.8E-16	-2.8E-15	9.2E-15
(NORMAL --> "x")	x^3	x^2	x	1

SURFACE AREA:
(model) 109.5519
(actual) 109.5519

OUTPUT: COEFF. OF (ACTUAL) INTERPOLATING POLYNOMIALS, U(X).

	A	B	C	D
0 to 1:	4.1E-18	0	-4.1E-18	0
1 to 2:	-9.4E-17	3.7E-16	-4.5E-16	1.7E-16
2 to 3:	1.6E-15	1.6E-15	-3.9E-15	3.1E-15
3 to 4:	1	-9	27	-27
4 to 5:	-3	39	-165	229
5 to 6:	3	-51	285	-521
6 to 7:	-1	21	-147	343
7 to 8:	1.8E-16	-4.0E-15	3.0E-14	-7.6E-14
8 to 9:	4.2E-17	-1.1E-15	9.8E-15	-2.9E-14
9 - 10:	-9.3E-18	2.8E-16	-2.8E-15	9.2E-15
(ACTUAL --> "X")	X^3	X^2	X	1

LAMDA: 1

RELATIONS:

```
LET lamda = 1
THEN:            X = 1*x
AND:          U(X) = 1*U(x)
THEREFORE        A = a/1^2
                 B = b/1
                 C = c
                 D = d*1
```

2	1	0	0	0	0	0	0	0	0	0
1	4	1	0	0	0	0	0	0	0	0
0	1	4	1	0	0	0	0	0	0	0
0	0	1	4	1	0	0	0	0	0	0
0	0	0	1	4	1	0	0	0	0	0
0	0	0	0	1	4	1	0	0	0	0
0	0	0	0	0	1	4	1	0	0	0
0	0	0	0	0	0	1	4	1	0	0
0	0	0	0	0	0	0	1	4	1	0
0	0	0	0	0	0	0	0	1	4	1
0	0	0	0	0	0	0	0	0	1	2

(11x11 CUBIC SPLINE SLOPE MATRIX.)
[A]

0.577	-0.15	0.041	-0.01	0.002	-0.00	0.000	-0.00	0.000015	-0.00	0.000
-0.15	0.309	-0.08	0.022	-0.00	0.001	-0.00	0.000	-0.00003	0.000	-0.00
0.041	-0.08	0.290	-0.07	0.020	-0.00	0.001	-0.00	0.000107	-0.00	0.000
-0.01	0.022	-0.07	0.288	-0.07	0.020	-0.00	0.001	-0.00040	0.000	-0.00
0.002	-0.00	0.020	-0.07	0.288	-0.07	0.020	-0.00	0.001495	-0.00	0.000
-0.00	0.001	-0.00	0.020	-0.07	0.288	-0.07	0.020	-0.00558	0.001	-0.00
0.000	-0.00	0.001	-0.00	0.020	-0.07	0.288	-0.07	0.020832	-0.00	0.002
-0.00	0.000	-0.00	0.001	-0.00	0.020	-0.07	0.288	-0.07774	0.022	-0.01
0.000	-0.00	0.000	-0.00	0.001	-0.00	0.020	-0.07	0.290163	-0.08	0.041
-0.00	0.000	-0.00	0.000	-0.00	0.001	-0.00	0.022	-0.08290	0.309	-0.15
0.000	-0.00	0.000	-0.00	0.000	-0.00	0.002	-0.01	0.041451	-0.15	0.577

(INVERTED 11x11 MATRIX FROM ABOVE.)
[A]^-1

THE FORMULA FOR CALCULATING THE SPLINE FUNCTIONS:

[A]^-1 x 3[U] = [S]

[U] IS THE INPUT MATRIX
[S] IS THE RESULTING SLOPE MATRIX
[A] IS THE CUBIC SPLINE SLOPE MATRIX

[U]	[S]
0	-4.1E-18
0	8.2E-18
0	-1.0E-16
3	-1.1E-16
12	3
0	1.0E-17
-12	-3
-3	1.2E-16
0	6.1E-17
0	-1.9E-17
0	9.3E-18

SUB-STATION NUMBER:	a ****** x^3	b 0 x^2	c ****** x^1	d 0 x^0	0 TO 1 U(x)	L(i)	AVG RADIUS	SURF AREA
0	0	0	0	1	0			
0.02	0.000	0.000	0.02	1	-8.2E-20	0.01	4.1E-20	2.6E-21
0.04	0.000	0.001	0.04	1	-1.6E-19	0.01	1.2E-19	7.7E-21
0.06	0.000	0.003	0.06	1	-2.4E-19	0.01	2.0E-19	1.3E-20
0.08	0.000	0.006	0.08	1	-3.2E-19	0.01	2.8E-19	1.8E-20
0.1	0.001	0.01	0.1	1	-4.0E-19	0.01	3.6E-19	2.3E-20
0.12	0.001	0.014	0.12	1	-4.8E-19	0.01	4.4E-19	2.8E-20
0.14	0.002	0.019	0.14	1	-5.6E-19	0.01	5.2E-19	3.3E-20
0.16	0.004	0.025	0.16	1	-6.4E-19	0.01	6.0E-19	3.8E-20
0.18	0.005	0.032	0.18	1	-7.1E-19	0.01	6.7E-19	4.2E-20
0.2	0.008	0.04	0.2	1	-7.8E-19	0.01	7.5E-19	4.7E-20
0.22	0.010	0.048	0.22	1	-8.6E-19	0.01	8.2E-19	5.2E-20
0.24	0.013	0.057	0.24	1	-9.2E-19	0.01	8.9E-19	5.6E-20
0.26	0.017	0.067	0.26	1	-9.9E-19	0.01	9.6E-19	6.0E-20
0.28	0.021	0.078	0.28	1	-1.1E-18	0.01	1.0E-18	6.4E-20
0.3	0.027	0.09	0.3	1	-1.1E-18	0.01	1.1E-18	6.8E-20
0.32	0.032	0.102	0.32	1	-1.2E-18	0.01	1.1E-18	7.2E-20
0.34	0.039	0.115	0.34	1	-1.2E-18	0.01	1.2E-18	7.5E-20
0.36	0.046	0.129	0.36	1	-1.3E-18	0.01	1.3E-18	7.9E-20
0.38	0.054	0.144	0.38	1	-1.3E-18	0.01	1.3E-18	8.2E-20
0.4	0.064	0.16	0.4	1	-1.4E-18	0.01	1.4E-18	8.5E-20
0.42	0.074	0.176	0.42	1	-1.4E-18	0.01	1.4E-18	8.8E-20
0.44	0.085	0.193	0.44	1	-1.4E-18	0.01	1.4E-18	9.0E-20
0.46	0.097	0.211	0.46	1	-1.5E-18	0.01	1.5E-18	9.2E-20
0.48	0.110	0.230	0.48	1	-1.5E-18	0.01	1.5E-18	9.4E-20
0.5	0.125	0.25	0.5	1	-1.5E-18	0.01	1.5E-18	9.6E-20
0.52	0.140	0.270	0.52	1	-1.6E-18	0.01	1.5E-18	9.7E-20
0.54	0.157	0.291	0.54	1	-1.6E-18	0.01	1.6E-18	9.8E-20
0.56	0.175	0.313	0.56	1	-1.6E-18	0.01	1.6E-18	9.8E-20
0.58	0.195	0.336	0.58	1	-1.6E-18	0.01	1.6E-18	9.9E-20
0.6	0.216	0.36	0.6	1	-1.6E-18	0.01	1.6E-18	9.9E-20
0.62	0.238	0.384	0.62	1	-1.6E-18	0.01	1.6E-18	9.8E-20
0.64	0.262	0.409	0.64	1	-1.5E-18	0.01	1.6E-18	9.7E-20
0.66	0.287	0.435	0.66	1	-1.5E-18	0.01	1.5E-18	9.6E-20
0.68	0.314	0.462	0.68	1	-1.5E-18	0.01	1.5E-18	9.5E-20
0.7	0.343	0.49	0.7	1	-1.5E-18	0.01	1.5E-18	9.3E-20
0.72	0.373	0.518	0.72	1	-1.4E-18	0.01	1.4E-18	9.0E-20
0.74	0.405	0.547	0.74	1	-1.4E-18	0.01	1.4E-18	8.7E-20
0.76	0.438	0.577	0.76	1	-1.3E-18	0.01	1.3E-18	8.4E-20
0.78	0.474	0.608	0.78	1	-1.2E-18	0.01	1.3E-18	8.0E-20
0.8	0.512	0.64	0.8	1	-1.2E-18	0.01	1.2E-18	7.6E-20
0.82	0.551	0.672	0.82	1	-1.1E-18	0.01	1.1E-18	7.1E-20
0.84	0.592	0.705	0.84	1	-1.0E-18	0.01	1.1E-18	6.6E-20
0.86	0.636	0.739	0.86	1	-9.2E-19	0.01	9.6E-19	6.0E-20
0.88	0.681	0.774	0.88	1	-8.1E-19	0.01	8.6E-19	5.4E-20
0.9	0.729	0.81	0.9	1	-7.0E-19	0.01	7.5E-19	4.7E-20
0.92	0.778	0.846	0.92	1	-5.8E-19	0.01	6.4E-19	4.0E-20
0.94	0.830	0.883	0.94	1	-4.5E-19	0.01	5.1E-19	3.2E-20
0.96	0.884	0.921	0.96	1	-3.1E-19	0.01	3.8E-19	2.4E-20
0.98	0.941	0.960	0.98	1	-1.6E-19	0.01	2.3E-19	1.5E-20
1	1	1	1	1	0	0.01	7.9E-20	5.0E-21
							TOTAL:	3.2E-18

SUB-STATION NUMBER:	a x^3	b x^2	c x^1	d x^0	U(x)	1 TO 2 L(i)	AVG RADIUS	SURF AREA
1	1	1	1	1	0			
1.02	1.061	1.040	1.02	1	2.0E-19	0.02	9.9E-20	1.2E-20
1.04	1.124	1.081	1.04	1	4.6E-19	0.02	3.3E-19	4.1E-20
1.06	1.191	1.123	1.06	1	7.8E-19	0.02	6.2E-19	7.8E-20
1.08	1.259	1.166	1.08	1	1.2E-18	0.02	9.7E-19	1.2E-19
1.1	1.331	1.21	1.1	1	1.6E-18	0.02	1.4E-18	1.7E-19
1.12	1.404	1.254	1.12	1	2.1E-18	0.02	1.8E-18	2.3E-19
1.14	1.481	1.299	1.14	1	2.6E-18	0.02	2.3E-18	2.9E-19
1.16	1.560	1.345	1.16	1	3.1E-18	0.02	2.8E-18	3.6E-19
1.18	1.643	1.392	1.18	1	3.7E-18	0.02	3.4E-18	4.3E-19
1.2	1.728	1.44	1.2	1	4.3E-18	0.02	4.0E-18	5.0E-19
1.22	1.815	1.488	1.22	1	5.0E-18	0.02	4.6E-18	5.8E-19
1.24	1.906	1.537	1.24	1	5.6E-18	0.02	5.3E-18	6.6E-19
1.26	2.000	1.587	1.26	1	6.3E-18	0.02	6.0E-18	7.5E-19
1.28	2.097	1.638	1.28	1	7.0E-18	0.02	6.6E-18	8.3E-19
1.3	2.197	1.69	1.3	1	7.7E-18	0.02	7.3E-18	9.2E-19
1.32	2.299	1.742	1.32	1	8.3E-18	0.02	8.0E-18	1.0E-18
1.34	2.406	1.795	1.34	1	9.0E-18	0.02	8.7E-18	1.1E-18
1.36	2.515	1.849	1.36	1	9.7E-18	0.02	9.4E-18	1.2E-18
1.38	2.628	1.904	1.38	1	1.0E-17	0.02	1.0E-17	1.3E-18
1.4	2.744	1.96	1.4	1	1.1E-17	0.02	1.1E-17	1.3E-18
1.42	2.863	2.016	1.42	1	1.2E-17	0.02	1.1E-17	1.4E-18
1.44	2.985	2.073	1.44	1	1.2E-17	0.02	1.2E-17	1.5E-18
1.46	3.112	2.131	1.46	1	1.3E-17	0.02	1.3E-17	1.6E-18
1.48	3.241	2.190	1.48	1	1.3E-17	0.02	1.3E-17	1.6E-18
1.5	3.375	2.25	1.5	1	1.4E-17	0.02	1.4E-17	1.7E-18
1.52	3.511	2.310	1.52	1	1.4E-17	0.02	1.4E-17	1.8E-18
1.54	3.652	2.371	1.54	1	1.5E-17	0.02	1.4E-17	1.8E-18
1.56	3.796	2.433	1.56	1	1.5E-17	0.02	1.5E-17	1.9E-18
1.58	3.944	2.496	1.58	1	1.5E-17	0.02	1.5E-17	1.9E-18
1.6	4.096	2.56	1.6	1	1.6E-17	0.02	1.5E-17	1.9E-18
1.62	4.251	2.624	1.62	1	1.6E-17	0.02	1.6E-17	2.0E-18
1.64	4.410	2.689	1.64	1	1.6E-17	0.02	1.6E-17	2.0E-18
1.66	4.574	2.755	1.66	1	1.6E-17	0.02	1.6E-17	2.0E-18
1.68	4.741	2.822	1.68	1	1.6E-17	0.02	1.6E-17	2.0E-18
1.7	4.913	2.89	1.7	1	1.6E-17	0.02	1.6E-17	2.0E-18
1.72	5.088	2.958	1.72	1	1.5E-17	0.02	1.5E-17	1.9E-18
1.74	5.268	3.027	1.74	1	1.5E-17	0.02	1.5E-17	1.9E-18
1.76	5.451	3.097	1.76	1	1.5E-17	0.02	1.5E-17	1.9E-18
1.78	5.639	3.168	1.78	1	1.4E-17	0.02	1.4E-17	1.8E-18
1.8	5.832	3.24	1.8	1	1.3E-17	0.02	1.4E-17	1.7E-18
1.82	6.028	3.312	1.82	1	1.3E-17	0.02	1.3E-17	1.6E-18
1.84	6.229	3.385	1.84	1	1.2E-17	0.02	1.2E-17	1.5E-18
1.86	6.434	3.459	1.86	1	1.1E-17	0.02	1.1E-17	1.4E-18
1.88	6.644	3.534	1.88	1	9.6E-18	0.02	1.0E-17	1.3E-18
1.9	6.859	3.61	1.9	1	8.4E-18	0.02	9.0E-18	1.1E-18
1.92	7.077	3.686	1.92	1	7.0E-18	0.02	7.7E-18	9.6E-19
1.94	7.301	3.763	1.94	1	5.5E-18	0.02	6.2E-18	7.8E-19
1.96	7.529	3.841	1.96	1	3.8E-18	0.02	4.6E-18	5.8E-19
1.98	7.762	3.920	1.98	1	2.0E-18	0.02	2.9E-18	3.6E-19
2	8	4	2	1	0	0.02	9.9E-19	1.2E-19
							TOTAL:	5.8E-17

SUB-STATION NUMBER:	a x^3	b x^2	c x^1	d x^0	U(x)	L(i)	AVG RADIUS	SURF AREA
					2 TO 3			
2	8	4	2	1	0			
2.02	8.242	4.080	2.02	1	-1.9E-18	0.02	9.6E-19	1.2E-19
2.04	8.489	4.161	2.04	1	-3.6E-18	0.02	2.8E-18	3.5E-19
2.06	8.741	4.243	2.06	1	-5.1E-18	0.02	4.3E-18	5.5E-19
2.08	8.998	4.326	2.08	1	-6.3E-18	0.02	5.7E-18	7.2E-19
2.1	9.261	4.41	2.1	1	-7.3E-18	0.02	6.8E-18	8.6E-19
2.12	9.528	4.494	2.12	1	-8.2E-18	0.02	7.8E-18	9.7E-19
2.14	9.800	4.579	2.14	1	-8.8E-18	0.02	8.5E-18	1.1E-18
2.16	10.07	4.665	2.16	1	-9.3E-18	0.02	9.0E-18	1.1E-18
2.18	10.36	4.752	2.18	1	-9.6E-18	0.02	9.4E-18	1.2E-18
2.2	10.64	4.84	2.2	1	-9.7E-18	0.02	9.6E-18	1.2E-18
2.22	10.94	4.928	2.22	1	-9.7E-18	0.02	9.7E-18	1.2E-18
2.24	11.23	5.017	2.24	1	-9.5E-18	0.02	9.6E-18	1.2E-18
2.26	11.54	5.107	2.26	1	-9.3E-18	0.02	9.4E-18	1.2E-18
2.28	11.85	5.198	2.28	1	-8.8E-18	0.02	9.1E-18	1.1E-18
2.3	12.16	5.29	2.3	1	-8.3E-18	0.02	8.6E-18	1.1E-18
2.32	12.48	5.382	2.32	1	-7.7E-18	0.02	8.0E-18	1.0E-18
2.34	12.81	5.475	2.34	1	-7.0E-18	0.02	7.4E-18	9.3E-19
2.36	13.14	5.569	2.36	1	-6.3E-18	0.02	6.6E-18	8.4E-19
2.38	13.48	5.664	2.38	1	-5.4E-18	0.02	5.8E-18	7.3E-19
2.4	13.82	5.76	2.4	1	-4.5E-18	0.02	5.0E-18	6.2E-19
2.42	14.17	5.856	2.42	1	-3.6E-18	0.02	4.0E-18	5.1E-19
2.44	14.52	5.953	2.44	1	-2.6E-18	0.02	3.1E-18	3.9E-19
2.46	14.88	6.051	2.46	1	-1.6E-18	0.02	2.1E-18	2.6E-19
2.48	15.25	6.150	2.48	1	-5.2E-19	0.02	1.0E-18	1.3E-19
2.5	15.62	6.25	2.5	1	5.3E-19	0.02	6.1E-21	7.7E-22
2.52	16.00	6.350	2.52	1	1.6E-18	0.02	1.1E-18	1.3E-19
2.54	16.38	6.451	2.54	1	2.6E-18	0.02	2.1E-18	2.6E-19
2.56	16.77	6.553	2.56	1	3.6E-18	0.02	3.1E-18	3.9E-19
2.58	17.17	6.656	2.58	1	4.6E-18	0.02	4.1E-18	5.2E-19
2.6	17.57	6.76	2.6	1	5.5E-18	0.02	5.1E-18	6.4E-19
2.62	17.98	6.864	2.62	1	6.4E-18	0.02	6.0E-18	7.5E-19
2.64	18.39	6.969	2.64	1	7.2E-18	0.02	6.8E-18	8.6E-19
2.66	18.82	7.075	2.66	1	8.0E-18	0.02	7.6E-18	9.6E-19
2.68	19.24	7.182	2.68	1	8.7E-18	0.02	8.3E-18	1.0E-18
2.7	19.68	7.29	2.7	1	9.2E-18	0.02	8.9E-18	1.1E-18
2.72	20.12	7.398	2.72	1	9.7E-18	0.02	9.5E-18	1.2E-18
2.74	20.57	7.507	2.74	1	1.0E-17	0.02	9.9E-18	1.2E-18
2.76	21.02	7.617	2.76	1	1.0E-17	0.02	1.0E-17	1.3E-18
2.78	21.48	7.728	2.78	1	1.0E-17	0.02	1.0E-17	1.3E-18
2.8	21.95	7.84	2.8	1	1.0E-17	0.02	1.0E-17	1.3E-18
2.82	22.42	7.952	2.82	1	1.0E-17	0.02	1.0E-17	1.3E-18
2.84	22.90	8.065	2.84	1	9.8E-18	0.02	1.0E-17	1.3E-18
2.86	23.39	8.179	2.86	1	9.3E-18	0.02	9.6E-18	1.2E-18
2.88	23.88	8.294	2.88	1	8.6E-18	0.02	9.0E-18	1.1E-18
2.9	24.38	8.41	2.9	1	7.7E-18	0.02	8.2E-18	1.0E-18
2.92	24.89	8.526	2.92	1	6.6E-18	0.02	7.2E-18	9.0E-19
2.94	25.41	8.643	2.94	1	5.3E-18	0.02	6.0E-18	7.5E-19
2.96	25.93	8.761	2.96	1	3.8E-18	0.02	4.5E-18	5.7E-19
2.98	26.46	8.880	2.98	1	2.0E-18	0.02	2.9E-18	3.6E-19
3	27	9	3	1	0	0.02	1.0E-18	1.3E-19
							TOTAL:	4.1E-17

	a	b	c	d	3 TO 4			
SUB-	1	-9	27	-27				
STATION NUMBER:	x^3	x^2	x^1	x^0	U(x)	L(i)	AVG RADIUS	SURF AREA
3	27	9	3	1	1.0E-15			
3.02	27.54	9.120	3.02	1	0.000008	0.020000	0.000004	0.000000
3.04	28.09	9.241	3.04	1	0.000064	0.020000	0.000036	0.000004
3.06	28.65	9.363	3.06	1	0.000216	0.020000	0.00014	0.000017
3.08	29.21	9.486	3.08	1	0.000512	0.020002	0.000364	0.000045
3.1	29.79	9.61	3.1	1	0.001	0.020005	0.000756	0.000095
3.12	30.37	9.734	3.12	1	0.001728	0.020013	0.001364	0.000171
3.14	30.95	9.859	3.14	1	0.002744	0.020025	0.002236	0.000281
3.16	31.55	9.985	3.16	1	0.004096	0.020045	0.00342	0.000430
3.18	32.15	10.11	3.18	1	0.005832	0.020075	0.004964	0.000626
3.2	32.76	10.24	3.2	1	0.008	0.020117	0.006916	0.000874
3.22	33.38	10.36	3.22	1	0.010648	0.020174	0.009324	0.001181
3.24	34.01	10.49	3.24	1	0.013824	0.020250	0.012236	0.001556
3.26	34.64	10.62	3.26	1	0.017576	0.020348	0.0157	0.002007
3.28	35.28	10.75	3.28	1	0.021952	0.020473	0.019764	0.002542
3.3	35.93	10.89	3.3	1	0.027	0.020627	0.024476	0.003172
3.32	36.59	11.02	3.32	1	0.032768	0.020815	0.029884	0.003908
3.34	37.25	11.15	3.34	1	0.039304	0.021040	0.036036	0.004764
3.36	37.93	11.28	3.36	1	0.046656	0.021308	0.04298	0.005754
3.38	38.61	11.42	3.38	1	0.054872	0.021621	0.050764	0.006896
3.4	39.30	11.56	3.4	1	0.064	0.021984	0.059436	0.008210
3.42	40.00	11.69	3.42	1	0.074088	0.022400	0.069044	0.009717
3.44	40.70	11.83	3.44	1	0.085184	0.022871	0.079636	0.011444
3.46	41.42	11.97	3.46	1	0.097336	0.023402	0.09126	0.013419
3.48	42.14	12.11	3.48	1	0.110592	0.023994	0.103964	0.015673
3.5	42.87	12.25	3.5	1	0.125	0.024649	0.117796	0.018243
3.52	43.61	12.39	3.52	1	0.140608	0.025369	0.132804	0.021169
3.54	44.36	12.53	3.54	1	0.157464	0.026155	0.149036	0.024492
3.56	45.11	12.67	3.56	1	0.175616	0.027009	0.16654	0.028262
3.58	45.88	12.81	3.58	1	0.195112	0.027930	0.185364	0.032529
3.6	46.65	12.96	3.6	1	0.216	0.028918	0.205556	0.037350
3.62	47.43	13.10	3.62	1	0.238328	0.029975	0.227164	0.042784
3.64	48.22	13.24	3.64	1	0.262144	0.031099	0.250236	0.048897
3.66	49.02	13.39	3.66	1	0.287496	0.032291	0.27482	0.055758
3.68	49.83	13.54	3.68	1	0.314432	0.033549	0.300964	0.063441
3.7	50.65	13.69	3.7	1	0.343	0.034873	0.328716	0.072026
3.72	51.47	13.83	3.72	1	0.373248	0.036262	0.358124	0.081595
3.74	52.31	13.98	3.74	1	0.405224	0.037715	0.389236	0.092238
3.76	53.15	14.13	3.76	1	0.438976	0.039232	0.4221	0.104050
3.78	54.01	14.28	3.78	1	0.474552	0.040812	0.456764	0.117128
3.8	54.87	14.44	3.8	1	0.512	0.042454	0.493276	0.131579
3.82	55.74	14.59	3.82	1	0.551368	0.044156	0.531684	0.147513
3.84	56.62	14.74	3.84	1	0.592704	0.045920	0.572036	0.165046
3.86	57.51	14.89	3.86	1	0.636056	0.047743	0.61438	0.184300
3.88	58.41	15.05	3.88	1	0.681472	0.049624	0.658764	0.205403
3.9	59.31	15.21	3.9	1	0.729	0.051564	0.705236	0.228489
3.92	60.23	15.36	3.92	1	0.778688	0.053562	0.753844	0.253699
3.94	61.16	15.52	3.94	1	0.830584	0.055616	0.804636	0.281179
3.96	62.09	15.68	3.96	1	0.884736	0.057727	0.85766	0.311082
3.98	63.04	15.84	3.98	1	0.941192	0.059893	0.912964	0.343570
4	64	16	4	1	1	0.062115	0.970596	0.378809
							TOTAL:	3.563441

	a	b	c	d	4 TO 5			
SUB-	-3	39	-165	229				
STATION NUMBER:	x^3	x^2	x^1	x^0	U(x)	L(i)	AVG RADIUS	SURF AREA
4	64	16	4	1	1			
4.02	64.96	16.16	4.02	1	1.061176	0.064362	1.030588	0.416769
4.04	65.93	16.32	4.04	1	1.124608	0.066510	1.092892	0.456715
4.06	66.92	16.48	4.06	1	1.190152	0.068527	1.15738	0.498334
4.08	67.91	16.64	4.08	1	1.257664	0.070412	1.223908	0.541472
4.1	68.92	16.81	4.1	1	1.327	0.072162	1.292332	0.585959
4.12	69.93	16.97	4.12	1	1.398016	0.073778	1.362508	0.631609
4.14	70.95	17.13	4.14	1	1.470568	0.075258	1.434292	0.678220
4.16	71.99	17.30	4.16	1	1.544512	0.076601	1.50754	0.725576
4.18	73.03	17.47	4.18	1	1.619704	0.077806	1.582108	0.773448
4.2	74.08	17.64	4.2	1	1.696	0.078873	1.657852	0.821596
4.22	75.15	17.80	4.22	1	1.773256	0.079802	1.734628	0.869770
4.24	76.22	17.97	4.24	1	1.851328	0.080593	1.812292	0.917710
4.26	77.30	18.14	4.26	1	1.930072	0.081244	1.8907	0.965149
4.28	78.40	18.31	4.28	1	2.009344	0.081756	1.969708	1.011816
4.3	79.50	18.49	4.3	1	2.089	0.082128	2.049172	1.057430
4.32	80.62	18.66	4.32	1	2.168896	0.082361	2.128948	1.101711
4.34	81.74	18.83	4.34	1	2.248888	0.082454	2.208892	1.144373
4.36	82.88	19.00	4.36	1	2.328832	0.082407	2.28886	1.185133
4.38	84.02	19.18	4.38	1	2.408584	0.082221	2.368708	1.223705
4.4	85.18	19.36	4.4	1	2.488	0.081895	2.448292	1.259807
4.42	86.35	19.53	4.42	1	2.566936	0.081430	2.527468	1.293157
4.44	87.52	19.71	4.44	1	2.645248	0.080825	2.606092	1.323482
4.46	88.71	19.89	4.46	1	2.722792	0.080081	2.68402	1.350512
4.48	89.91	20.07	4.48	1	2.799424	0.079198	2.761108	1.373986
4.5	91.12	20.25	4.5	1	2.875	0.078177	2.837212	1.393650
4.52	92.34	20.43	4.52	1	2.949376	0.077018	2.912188	1.409263
4.54	93.57	20.61	4.54	1	3.022408	0.075721	2.985892	1.420595
4.56	94.81	20.79	4.56	1	3.093952	0.074286	3.05818	1.427431
4.58	96.07	20.97	4.58	1	3.163864	0.072716	3.128908	1.429570
4.6	97.33	21.16	4.6	1	3.232	0.071010	3.197932	1.426831
4.62	98.61	21.34	4.62	1	3.298216	0.069170	3.265108	1.419052
4.64	99.89	21.52	4.64	1	3.362368	0.067197	3.330292	1.406093
4.66	101.1	21.71	4.66	1	3.424312	0.065092	3.39334	1.387840
4.68	102.5	21.90	4.68	1	3.483904	0.062858	3.454108	1.364208
4.7	103.8	22.09	4.7	1	3.541	0.060497	3.512452	1.335143
4.72	105.1	22.27	4.72	1	3.595456	0.058012	3.568228	1.300631
4.74	106.4	22.46	4.74	1	3.647128	0.055407	3.621292	1.260701
4.76	107.8	22.65	4.76	1	3.695872	0.052687	3.6715	1.215433
4.78	109.2	22.84	4.78	1	3.741544	0.049859	3.718708	1.164974
4.8	110.5	23.04	4.8	1	3.784	0.046930	3.762772	1.109550
4.82	111.9	23.23	4.82	1	3.823096	0.043914	3.803548	1.049489
4.84	113.3	23.42	4.84	1	3.858688	0.040826	3.840892	0.985263
4.86	114.7	23.61	4.86	1	3.890632	0.037688	3.87466	0.917533
4.88	116.2	23.81	4.88	1	3.918784	0.034533	3.904708	0.847235
4.9	117.6	24.01	4.9	1	3.943	0.031407	3.930892	0.775712
4.92	119.0	24.20	4.92	1	3.963136	0.028380	3.953068	0.704913
4.94	120.5	24.40	4.94	1	3.979048	0.025557	3.971092	0.637690
4.96	122.0	24.60	4.96	1	3.990592	0.023092	3.98482	0.578175
4.98	123.5	24.80	4.98	1	3.997624	0.021200	3.994108	0.532034
5	125	25	5	1	4	0.020140	3.998812	0.506039
							TOTAL:	51.21251

SUB-STATION NUMBER:	a 3 x^3	b -51 x^2	c 285 x^1	d -521 x^0	5 TO 6 U(x)	L(i)	AVG RADIUS	SURF AREA
5	125	25	5	1	4			
5.02	126.5	25.20	5.02	1	3.997624	0.020140	3.998812	0.506039
5.04	128.0	25.40	5.04	1	3.990592	0.021200	3.994108	0.532034
5.06	129.5	25.60	5.06	1	3.979048	0.023092	3.98482	0.578175
5.08	131.0	25.80	5.08	1	3.963136	0.025557	3.971092	0.637690
5.1	132.6	26.01	5.1	1	3.943	0.028380	3.953068	0.704913
5.12	134.2	26.21	5.12	1	3.918784	0.031407	3.930892	0.775712
5.14	135.7	26.41	5.14	1	3.890632	0.034533	3.904708	0.847235
5.16	137.3	26.62	5.16	1	3.858688	0.037688	3.87466	0.917533
5.18	138.9	26.83	5.18	1	3.823096	0.040826	3.840892	0.985263
5.2	140.6	27.04	5.2	1	3.784	0.043914	3.803548	1.049489
5.22	142.2	27.24	5.22	1	3.741544	0.046930	3.762772	1.109550
5.24	143.8	27.45	5.24	1	3.695872	0.049859	3.718708	1.164974
5.26	145.5	27.66	5.26	1	3.647128	0.052687	3.6715	1.215433
5.28	147.1	27.87	5.28	1	3.595456	0.055407	3.621292	1.260701
5.3	148.8	28.09	5.3	1	3.541	0.058012	3.568228	1.300631
5.32	150.5	28.30	5.32	1	3.483904	0.060497	3.512452	1.335143
5.34	152.2	28.51	5.34	1	3.424312	0.062858	3.454108	1.364208
5.36	153.9	28.72	5.36	1	3.362368	0.065092	3.39334	1.387840
5.38	155.7	28.94	5.38	1	3.298216	0.067197	3.330292	1.406093
5.4	157.4	29.16	5.4	1	3.232	0.069170	3.265108	1.419052
5.42	159.2	29.37	5.42	1	3.163864	0.071010	3.197932	1.426831
5.44	160.9	29.59	5.44	1	3.093952	0.072716	3.128908	1.429570
5.46	162.7	29.81	5.46	1	3.022408	0.074286	3.05818	1.427431
5.48	164.5	30.03	5.48	1	2.949376	0.075721	2.985892	1.420595
5.5	166.3	30.25	5.5	1	2.875	0.077018	2.912188	1.409263
5.52	168.1	30.47	5.52	1	2.799424	0.078177	2.837212	1.393650
5.54	170.0	30.69	5.54	1	2.722792	0.079198	2.761108	1.373986
5.56	171.8	30.91	5.56	1	2.645248	0.080081	2.68402	1.350512
5.58	173.7	31.13	5.58	1	2.566936	0.080825	2.606092	1.323482
5.6	175.6	31.36	5.6	1	2.488	0.081430	2.527468	1.293157
5.62	177.5	31.58	5.62	1	2.408584	0.081895	2.448292	1.259807
5.64	179.4	31.80	5.64	1	2.328832	0.082221	2.368708	1.223705
5.66	181.3	32.03	5.66	1	2.248888	0.082407	2.28886	1.185133
5.68	183.2	32.26	5.68	1	2.168896	0.082454	2.208892	1.144373
5.7	185.1	32.49	5.7	1	2.089	0.082361	2.128948	1.101711
5.72	187.1	32.71	5.72	1	2.009344	0.082128	2.049172	1.057430
5.74	189.1	32.94	5.74	1	1.930072	0.081756	1.969708	1.011816
5.76	191.1	33.17	5.76	1	1.851328	0.081244	1.8907	0.965149
5.78	193.1	33.40	5.78	1	1.773256	0.080593	1.812292	0.917710
5.8	195.1	33.64	5.8	1	1.696	0.079802	1.734628	0.869770
5.82	197.1	33.87	5.82	1	1.619704	0.078873	1.657852	0.821596
5.84	199.1	34.10	5.84	1	1.544512	0.077806	1.582108	0.773448
5.86	201.2	34.33	5.86	1	1.470568	0.076601	1.50754	0.725576
5.88	203.2	34.57	5.88	1	1.398016	0.075258	1.434292	0.678220
5.9	205.3	34.81	5.9	1	1.327	0.073776	1.362508	0.631609
5.92	207.4	35.04	5.92	1	1.257664	0.072162	1.292332	0.585959
5.94	209.5	35.28	5.94	1	1.190152	0.070412	1.223908	0.541472
5.96	211.7	35.52	5.96	1	1.124608	0.068527	1.15738	0.498334
5.98	213.8	35.76	5.98	1	1.061176	0.066510	1.092892	0.456715
6	216	36	6	1	1	0.064362	1.030588	0.416769
							TOTAL:	51.21251

	a	b	c	d	6 TO 7			
SUB-	-1	21	-147	343				
STATION NUMBER:	x^3	x^2	x^1	x^0	U(x)	L(i)	AVG RADIUS	SURF AREA
6	216	36	6	1	1			
6.02	218.1	36.24	6.02	1	0.941192	0.062115	0.970596	0.378809
6.04	220.3	36.48	6.04	1	0.884736	0.059893	0.912964	0.343570
6.06	222.5	36.72	6.06	1	0.830584	0.057727	0.85766	0.311082
6.08	224.7	36.96	6.08	1	0.778688	0.055616	0.804636	0.281179
6.1	226.9	37.21	6.1	1	0.729	0.053562	0.753844	0.253699
6.12	229.2	37.45	6.12	1	0.681472	0.051564	0.705236	0.228489
6.14	231.4	37.69	6.14	1	0.636056	0.049624	0.658764	0.205403
6.16	233.7	37.94	6.16	1	0.592704	0.047743	0.61438	0.184300
6.18	236.0	38.19	6.18	1	0.551368	0.045920	0.572036	0.165046
6.2	238.3	38.44	6.2	1	0.512	0.044156	0.531684	0.147513
6.22	240.6	38.68	6.22	1	0.474552	0.042454	0.493276	0.131579
6.24	242.9	38.93	6.24	1	0.438976	0.040812	0.456764	0.117128
6.26	245.3	39.18	6.26	1	0.405224	0.039232	0.4221	0.104050
6.28	247.6	39.43	6.28	1	0.373248	0.037715	0.389236	0.092238
6.3	250.0	39.69	6.3	1	0.343	0.036262	0.358124	0.081595
6.32	252.4	39.94	6.32	1	0.314432	0.034873	0.328716	0.072026
6.34	254.8	40.19	6.34	1	0.287496	0.033549	0.300964	0.063441
6.36	257.2	40.44	6.36	1	0.262144	0.032291	0.27482	0.055758
6.38	259.6	40.70	6.38	1	0.238328	0.031099	0.250236	0.048897
6.4	262.1	40.96	6.4	1	0.216	0.029975	0.227164	0.042784
6.42	264.6	41.21	6.42	1	0.195112	0.028918	0.205556	0.037350
6.44	267.0	41.47	6.44	1	0.175616	0.027930	0.185364	0.032529
6.46	269.5	41.73	6.46	1	0.157464	0.027009	0.16654	0.028262
6.48	272.0	41.99	6.48	1	0.140608	0.026155	0.149036	0.024492
6.5	274.6	42.25	6.5	1	0.125	0.025369	0.132804	0.021169
6.52	277.1	42.51	6.52	1	0.110592	0.024649	0.117796	0.018243
6.54	279.7	42.77	6.54	1	0.097336	0.023994	0.103964	0.015673
6.56	282.3	43.03	6.56	1	0.085184	0.023402	0.09126	0.013419
6.58	284.8	43.29	6.58	1	0.074088	0.022871	0.079636	0.011444
6.6	287.4	43.56	6.6	1	0.064	0.022400	0.069044	0.009717
6.62	290.1	43.82	6.62	1	0.054872	0.021984	0.059436	0.008210
6.64	292.7	44.08	6.64	1	0.046656	0.021621	0.050764	0.006896
6.66	295.4	44.35	6.66	1	0.039304	0.021308	0.04298	0.005754
6.68	298.0	44.62	6.68	1	0.032768	0.021040	0.036036	0.004764
6.7	300.7	44.89	6.7	1	0.027	0.020815	0.029884	0.003908
6.72	303.4	45.15	6.72	1	0.021952	0.020627	0.024476	0.003172
6.74	306.1	45.42	6.74	1	0.017576	0.020473	0.019764	0.002542
6.76	308.9	45.69	6.76	1	0.013824	0.020348	0.0157	0.002007
6.78	311.6	45.96	6.78	1	0.010648	0.020250	0.012236	0.001556
6.8	314.4	46.24	6.8	1	0.008	0.020174	0.009324	0.001181
6.82	317.2	46.51	6.82	1	0.005832	0.020117	0.006916	0.000874
6.84	320.0	46.78	6.84	1	0.004096	0.020075	0.004964	0.000626
6.86	322.8	47.05	6.86	1	0.002744	0.020045	0.00342	0.000430
6.88	325.6	47.33	6.88	1	0.001728	0.020025	0.002236	0.000281
6.9	328.5	47.61	6.9	1	0.001	0.020013	0.001364	0.000171
6.92	331.3	47.88	6.92	1	0.000512	0.020005	0.000756	0.000095
6.94	334.2	48.16	6.94	1	0.000216	0.020002	0.000364	0.000045
6.96	337.1	48.44	6.96	1	0.000064	0.020000	0.00014	0.000017
6.98	340.0	48.72	6.98	1	0.000008	0.020000	0.000036	0.000004
7	343	49	7	1	9.4E-14	0.020000	0.000004	0.000000
							TOTAL:	3.563441

SUB-STATION NUMBER:	a x^3	b x^2	c x^1	d x^0	U(x)	7 TO 8 L(i)	AVG RADIUS	SURF AREA
7	343	49	7	1	0			
7.02	345.9	49.28	7.02	1	2.2E-18	0.02	1.1E-18	1.4E-19
7.04	348.9	49.56	7.04	1	4.2E-18	0.02	3.2E-18	4.1E-19
7.06	351.8	49.84	7.06	1	6.0E-18	0.02	5.1E-18	6.4E-19
7.08	354.8	50.12	7.08	1	7.6E-18	0.02	6.8E-18	8.5E-19
7.1	357.9	50.41	7.1	1	8.9E-18	0.02	8.3E-18	1.0E-18
7.12	360.9	50.69	7.12	1	1.0E-17	0.02	9.5E-18	1.2E-18
7.14	363.9	50.97	7.14	1	1.1E-17	0.02	1.1E-17	1.3E-18
7.16	367.0	51.26	7.16	1	1.2E-17	0.02	1.2E-17	1.4E-18
7.18	370.1	51.55	7.18	1	1.3E-17	0.02	1.2E-17	1.5E-18
7.2	373.2	51.84	7.2	1	1.3E-17	0.02	1.3E-17	1.6E-18
7.22	376.3	52.12	7.22	1	1.3E-17	0.02	1.3E-17	1.7E-18
7.24	379.5	52.41	7.24	1	1.4E-17	0.02	1.3E-17	1.7E-18
7.26	382.6	52.70	7.26	1	1.4E-17	0.02	1.4E-17	1.7E-18
7.28	385.8	52.99	7.28	1	1.4E-17	0.02	1.4E-17	1.7E-18
7.3	389.0	53.29	7.3	1	1.3E-17	0.02	1.3E-17	1.7E-18
7.32	392.2	53.58	7.32	1	1.3E-17	0.02	1.3E-17	1.7E-18
7.34	395.4	53.87	7.34	1	1.3E-17	0.02	1.3E-17	1.6E-18
7.36	398.6	54.16	7.36	1	1.2E-17	0.02	1.2E-17	1.6E-18
7.38	401.9	54.46	7.38	1	1.2E-17	0.02	1.2E-17	1.5E-18
7.4	405.2	54.76	7.4	1	1.1E-17	0.02	1.1E-17	1.4E-18
7.42	408.5	55.05	7.42	1	1.0E-17	0.02	1.1E-17	1.3E-18
7.44	411.8	55.35	7.44	1	9.6E-18	0.02	1.0E-17	1.3E-18
7.46	415.1	55.65	7.46	1	8.8E-18	0.02	9.2E-18	1.2E-18
7.48	418.5	55.95	7.48	1	7.9E-18	0.02	8.4E-18	1.0E-18
7.5	421.8	56.25	7.5	1	7.1E-18	0.02	7.5E-18	9.4E-19
7.52	425.2	56.55	7.52	1	6.2E-18	0.02	6.6E-18	8.3E-19
7.54	428.6	56.85	7.54	1	5.2E-18	0.02	5.7E-18	7.2E-19
7.56	432.0	57.15	7.56	1	4.3E-18	0.02	4.8E-18	6.0E-19
7.58	435.5	57.45	7.58	1	3.4E-18	0.02	3.9E-18	4.9E-19
7.6	438.9	57.76	7.6	1	2.5E-18	0.02	3.0E-18	3.7E-19
7.62	442.4	58.06	7.62	1	1.6E-18	0.02	2.1E-18	2.6E-19
7.64	445.9	58.36	7.64	1	7.7E-19	0.02	1.2E-18	1.5E-19
7.66	449.4	58.67	7.66	1	-5.0E-20	0.02	3.6E-19	4.5E-20
7.68	452.9	58.98	7.68	1	-8.2E-19	0.02	4.4E-19	5.5E-20
7.7	456.5	59.29	7.7	1	-1.5E-18	0.02	1.2E-18	1.5E-19
7.72	460.0	59.59	7.72	1	-2.2E-18	0.02	1.9E-18	2.3E-19
7.74	463.6	59.90	7.74	1	-2.8E-18	0.02	2.5E-18	3.1E-19
7.76	467.2	60.21	7.76	1	-3.3E-18	0.02	3.0E-18	3.8E-19
7.78	470.9	60.52	7.78	1	-3.7E-18	0.02	3.5E-18	4.4E-19
7.8	474.5	60.84	7.8	1	-4.0E-18	0.02	3.9E-18	4.8E-19
7.82	478.2	61.15	7.82	1	-4.2E-18	0.02	4.1E-18	5.2E-19
7.84	481.8	61.46	7.84	1	-4.3E-18	0.02	4.3E-18	5.4E-19
7.86	485.5	61.77	7.86	1	-4.3E-18	0.02	4.3E-18	5.4E-19
7.88	489.3	62.09	7.88	1	-4.2E-18	0.02	4.2E-18	5.3E-19
7.9	493.0	62.41	7.9	1	-3.9E-18	0.02	4.0E-18	5.0E-19
7.92	496.7	62.72	7.92	1	-3.4E-18	0.02	3.6E-18	4.6E-19
7.94	500.5	63.04	7.94	1	-2.8E-18	0.02	3.1E-18	3.9E-19
7.96	504.3	63.36	7.96	1	-2.1E-18	0.02	2.4E-18	3.1E-19
7.98	508.1	63.68	7.98	1	-1.1E-18	0.02	1.6E-18	2.0E-19
8	512	64	8	1	0	0.02	5.6E-19	7.0E-20
							TOTAL:	4.2E-17

8 TO 9

SUB-STATION NUMBER:	a x^3	b x^2	c x^1	d x^0	U(x)	L(i)	AVG RADIUS	SURF AREA
8	512	64	8	1	0			
8.02	515.8	64.32	8.02	1	1.2E-18	0.02	5.9E-19	7.4E-20
8.04	519.7	64.64	8.04	1	2.3E-18	0.02	1.7E-18	2.2E-19
8.06	523.6	64.96	8.06	1	3.3E-18	0.02	2.8E-18	3.5E-19
8.08	527.5	65.28	8.08	1	4.2E-18	0.02	3.7E-18	4.7E-19
8.1	531.4	65.61	8.1	1	5.1E-18	0.02	4.6E-18	5.8E-19
8.12	535.3	65.93	8.12	1	5.9E-18	0.02	5.5E-18	6.9E-19
8.14	539.3	66.25	8.14	1	6.6E-18	0.02	6.2E-18	7.8E-19
8.16	543.3	66.58	8.16	1	7.2E-18	0.02	6.9E-18	8.7E-19
8.18	547.3	66.91	8.18	1	7.8E-18	0.02	7.5E-18	9.5E-19
8.2	551.3	67.24	8.2	1	8.4E-18	0.02	8.1E-18	1.0E-18
8.22	555.4	67.56	8.22	1	8.8E-18	0.02	8.6E-18	1.1E-18
8.24	559.4	67.89	8.24	1	9.2E-18	0.02	9.0E-18	1.1E-18
8.26	563.5	68.22	8.26	1	9.6E-18	0.02	9.4E-18	1.2E-18
8.28	567.6	68.55	8.28	1	9.9E-18	0.02	9.7E-18	1.2E-18
8.3	571.7	68.89	8.3	1	1.0E-17	0.02	1.0E-17	1.3E-18
8.32	575.9	69.22	8.32	1	1.0E-17	0.02	1.0E-17	1.3E-18
8.34	580.0	69.55	8.34	1	1.0E-17	0.02	1.0E-17	1.3E-18
8.36	584.2	69.88	8.36	1	1.0E-17	0.02	1.0E-17	1.3E-18
8.38	588.4	70.22	8.38	1	1.1E-17	0.02	1.1E-17	1.3E-18
8.4	592.7	70.56	8.4	1	1.1E-17	0.02	1.1E-17	1.3E-18
8.42	596.9	70.89	8.42	1	1.0E-17	0.02	1.0E-17	1.3E-18
8.44	601.2	71.23	8.44	1	1.0E-17	0.02	1.0E-17	1.3E-18
8.46	605.4	71.57	8.46	1	1.0E-17	0.02	1.0E-17	1.3E-18
8.48	609.8	71.91	8.48	1	1.0E-17	0.02	1.0E-17	1.3E-18
8.5	614.1	72.25	8.5	1	9.9E-18	0.02	1.0E-17	1.3E-18
8.52	618.4	72.59	8.52	1	9.7E-18	0.02	9.8E-18	1.2E-18
8.54	622.8	72.93	8.54	1	9.4E-18	0.02	9.5E-18	1.2E-18
8.56	627.2	73.27	8.56	1	9.1E-18	0.02	9.3E-18	1.2E-18
8.58	631.6	73.61	8.58	1	8.8E-18	0.02	9.0E-18	1.1E-18
8.6	636.0	73.96	8.6	1	8.5E-18	0.02	8.7E-18	1.1E-18
8.62	640.5	74.30	8.62	1	8.1E-18	0.02	8.3E-18	1.0E-18
8.64	644.9	74.64	8.64	1	7.8E-18	0.02	8.0E-18	1.0E-18
8.66	649.4	74.99	8.66	1	7.4E-18	0.02	7.6E-18	9.5E-19
8.68	653.9	75.34	8.68	1	7.0E-18	0.02	7.2E-18	9.0E-19
8.7	658.5	75.69	8.7	1	6.5E-18	0.02	6.8E-18	8.5E-19
8.72	663.0	76.03	8.72	1	6.1E-18	0.02	6.3E-18	8.0E-19
8.74	667.6	76.38	8.74	1	5.7E-18	0.02	5.9E-18	7.4E-19
8.76	672.2	76.73	8.76	1	5.2E-18	0.02	5.4E-18	6.8E-19
8.78	676.8	77.08	8.78	1	4.8E-18	0.02	5.0E-18	6.3E-19
8.8	681.4	77.44	8.8	1	4.3E-18	0.02	4.5E-18	5.7E-19
8.82	686.1	77.79	8.82	1	3.9E-18	0.02	4.1E-18	5.1E-19
8.84	690.8	78.14	8.84	1	3.4E-18	0.02	3.6E-18	4.6E-19
8.86	695.5	78.49	8.86	1	2.9E-18	0.02	3.2E-18	4.0E-19
8.88	700.2	78.85	8.88	1	2.5E-18	0.02	2.7E-18	3.4E-19
8.9	704.9	79.21	8.9	1	2.0E-18	0.02	2.3E-18	2.9E-19
8.92	709.7	79.56	8.92	1	1.6E-18	0.02	1.8E-18	2.3E-19
8.94	714.5	79.92	8.94	1	1.2E-18	0.02	1.4E-18	1.8E-19
8.96	719.3	80.28	8.96	1	7.8E-19	0.02	9.8E-19	1.2E-19
8.98	724.1	80.64	8.98	1	3.8E-19	0.02	5.8E-19	7.3E-20
9	729	81	9	1	0	0.02	1.9E-19	2.4E-20
							TOTAL:	4.1E-17

SUB- STATION NUMBER:	a x^3	b x^2	c x^1	d x^0	U(x)	9 TO 10 L(i)	AVG RADIUS	SURF AREA
9	729	81	9	1	0			
9.02	733.8	81.36	9.02	1	-3.6E-19	0.02	1.8E-19	2.3E-20
9.04	738.7	81.72	9.04	1	-7.0E-19	0.02	5.3E-19	6.6E-20
9.06	743.6	82.08	9.06	1	-1.0E-18	0.02	8.6E-19	1.1E-19
9.08	748.6	82.44	9.08	1	-1.3E-18	0.02	1.2E-18	1.5E-19
9.1	753.5	82.81	9.1	1	-1.6E-18	0.02	1.4E-18	1.8E-19
9.12	758.5	83.17	9.12	1	-1.8E-18	0.02	1.7E-18	2.2E-19
9.14	763.5	83.53	9.14	1	-2.1E-18	0.02	2.0E-18	2.5E-19
9.16	768.5	83.90	9.16	1	-2.3E-18	0.02	2.2E-18	2.7E-19
9.18	773.6	84.27	9.18	1	-2.5E-18	0.02	2.4E-18	3.0E-19
9.2	778.6	84.64	9.2	1	-2.7E-18	0.02	2.6E-18	3.2E-19
9.22	783.7	85.00	9.22	1	-2.8E-18	0.02	2.8E-18	3.5E-19
9.24	788.8	85.37	9.24	1	-3.0E-18	0.02	2.9E-18	3.6E-19
9.26	794.0	85.74	9.26	1	-3.1E-18	0.02	3.0E-18	3.8E-19
9.28	799.1	86.11	9.28	1	-3.2E-18	0.02	3.2E-18	4.0E-19
9.3	804.3	86.49	9.3	1	-3.3E-18	0.02	3.3E-18	4.1E-19
9.32	809.5	86.86	9.32	1	-3.4E-18	0.02	3.3E-18	4.2E-19
9.34	814.7	87.23	9.34	1	-3.5E-18	0.02	3.4E-18	4.3E-19
9.36	820.0	87.60	9.36	1	-3.5E-18	0.02	3.5E-18	4.4E-19
9.38	825.2	87.98	9.38	1	-3.5E-18	0.02	3.5E-18	4.4E-19
9.4	830.5	88.36	9.4	1	-3.6E-18	0.02	3.5E-18	4.5E-19
9.42	835.8	88.73	9.42	1	-3.6E-18	0.02	3.6E-18	4.5E-19
9.44	841.2	89.11	9.44	1	-3.6E-18	0.02	3.6E-18	4.5E-19
9.46	846.5	89.49	9.46	1	-3.5E-18	0.02	3.6E-18	4.5E-19
9.48	851.9	89.87	9.48	1	-3.5E-18	0.02	3.5E-18	4.4E-19
9.5	857.3	90.25	9.5	1	-3.5E-18	0.02	3.5E-18	4.4E-19
9.52	862.8	90.63	9.52	1	-3.4E-18	0.02	3.5E-18	4.3E-19
9.54	868.2	91.01	9.54	1	-3.4E-18	0.02	3.4E-18	4.3E-19
9.56	873.7	91.39	9.56	1	-3.3E-18	0.02	3.3E-18	4.2E-19
9.58	879.2	91.77	9.58	1	-3.2E-18	0.02	3.2E-18	4.1E-19
9.6	884.7	92.16	9.6	1	-3.1E-18	0.02	3.2E-18	4.0E-19
9.62	890.2	92.54	9.62	1	-3.0E-18	0.02	3.1E-18	3.9E-19
9.64	895.8	92.92	9.64	1	-2.9E-18	0.02	3.0E-18	3.7E-19
9.66	901.4	93.31	9.66	1	-2.8E-18	0.02	2.8E-18	3.6E-19
9.68	907.0	93.70	9.68	1	-2.7E-18	0.02	2.7E-18	3.4E-19
9.7	912.6	94.09	9.7	1	-2.5E-18	0.02	2.6E-18	3.3E-19
9.72	918.3	94.47	9.72	1	-2.4E-18	0.02	2.5E-18	3.1E-19
9.74	924.0	94.86	9.74	1	-2.2E-18	0.02	2.3E-18	2.9E-19
9.76	929.7	95.25	9.76	1	-2.1E-18	0.02	2.2E-18	2.7E-19
9.78	935.4	95.64	9.78	1	-1.9E-18	0.02	2.0E-18	2.5E-19
9.8	941.1	96.04	9.8	1	-1.8E-18	0.02	1.9E-18	2.3E-19
9.82	946.9	96.43	9.82	1	-1.6E-18	0.02	1.7E-18	2.1E-19
9.84	952.7	96.82	9.84	1	-1.4E-18	0.02	1.5E-18	1.9E-19
9.86	958.5	97.21	9.86	1	-1.3E-18	0.02	1.4E-18	1.7E-19
9.88	964.4	97.61	9.88	1	-1.1E-18	0.02	1.2E-18	1.5E-19
9.9	970.2	98.01	9.9	1	-9.2E-19	0.02	1.0E-18	1.3E-19
9.92	976.1	98.40	9.92	1	-7.4E-19	0.02	8.3E-19	1.0E-19
9.94	982.1	98.80	9.94	1	-5.5E-19	0.02	6.5E-19	8.1E-20
9.96	988.0	99.20	9.96	1	-3.7E-19	0.02	4.6E-19	5.8E-20
9.98	994.0	99.60	9.98	1	-1.9E-19	0.02	2.8E-19	3.5E-20
10	1000	100	10	1	0	0.02	9.3E-20	1.2E-20
							TOTAL:	1.5E-17

"HERMFAST.WK1" USED TO FIND THE INTERPOLATING POLYNOMIALS AND SURFACE AREA OF A BODY OF REVOLUTION.

The inputs are the station radii and slopes, and interstation distances. The outputs are cubic polynomials which describe the radius of the body between stations, and are used to calculate the body surface area. The generated polynomials and their first derivatives are CONTINUOUS over the length of the body, which is ideal for submarine surface area calculation.

CAUTION: IF THE ACTUAL INPUT BODY HAS DISCONTINUOUS FIRST DERIVATIVES, THE LOCATION OF THE SLOPE DISCONTINUITY SHOULD BE TREATED AS TWO VERY CLOSE STATIONS, EACH WITH ITS OWN SLOPE!

PROCEDURE:

(1) INPUT ACTUAL RADII, SLOPES, AND STATION SPACINGS.

(2) HIT [F9] TO CALCULATE INTERPOLATING COEFFICIENTS, AND AREAS.

INPUTS: INTER-VAL	ACTUAL INTERVAL LENGTH:	STATION	ACTUAL STATION RADIUS:	ACTUAL STATION SLOPE:		OUTPUT: ACTUAL SURFACE AREA	INTERVA
		0:	0	6	J		
0 TO 1	2	1:	4.21	1.3	.	68.62719	0 TO 1
1 TO 2	3.92	2:	7.78	0.9	K	202.5642	1 TO 2
2 TO 3	11.78	3:	12.01	0.01	.	858.7818	2 TO 3
3 TO 4	11.05	4:	12.5	0	S	852.4521	3 TO 4
4 TO 5	101.18	5:	12.5	0	.	7946.658	4 TO 5
5 TO 6	26.5	6:	11.95	-0.02		2043.290	5 TO 6
6 TO 7	24.81	7:	10.23	-0.09	1	1755.597	6 TO 7
7 TO 8	25.94	8:	6.48	-0.13	9	1389.976	7 TO 8
8 TO 9	23	9:	0	-0.25	8	519.0502	8 TO 9
9 TO 10	0.001	10:	0	0	8	0.000000	9 TO 10
	230.181 TOTAL LENGTH	18078.373 CYLYNDER SURFACE AREA	12.5 MAX RADIUS	=+=+=+=+=+ TYPE 2400 =+=+=+=+=+		15636.99	TOTAL
						588	other
						16224.99	GRAND

```
RELATIONS:
LET lamda = 1
THEN:            X = 1*x
AND:          U(X) = 1*U(x)
   SO:           A = a/1^2
   AND:          B = b/1
   AND:          C = c
   AND:          D = d*1
```

AUXILIARY OUTPUT

OUTPUT: COEFF. OF (ACTUAL) INTERPOLATING POLYNOMIALS, U(X).

	A	B	C	D
0 to 1:	7.73E-01	-3.49E+00	6.00E+00	0.00E+00
1 to 2:	2.46E-02	-4.86E-01	3.97E+00	-5.38E+00
2 to 3:	1.38E-03	-1.60E-01	6.13E+00	-6.60E+01
3 to 4:	-6.44E-04	7.43E-02	-2.79E+00	4.64E+01
4 to 5:	0.00E+00	0.00E+00	0.00E+00	1.25E+01
5 to 6:	3.06E-05	-1.38E-02	2.04E+00	-8.68E+01
6 to 7:	4.66E-05	-2.39E-02	4.01E+00	-2.08E+02
7 to 8:	1.03E-04	-6.07E-02	1.18E+01	-7.46E+02
8 to 9:	3.47E-04	-2.06E-01	4.05E+01	-2.62E+03
9 - 10:	-2.50E+05	7.25E+03	-7.00E+01	2.25E-01
(ACTUAL --> "X")	X^3	X^2	X	1

AUXILIARY OUTPUT

OUTPUT: COEFF. OF (NORMAL) INTERPOLATING POLYNOMIALS, U(x).

	a	b	c	d
0 to 1:	3.09	-6.985	6	0
1 to 2:	0.3785714	-1.903571	3.9714285	-1.372448
2 to 3:	0.1918336	-1.883752	6.1330050	-5.605229
3 to 4:	-0.078687	0.8212217	-2.792760	4.1987330
4 to 5:	0	0	0	0.1235422
5 to 6:	0.0215094	-0.364905	2.0358490	-3.273584
6 to 7:	0.0286537	-0.593748	4.0103748	-8.394856
7 to 8:	0.0691287	-1.575397	11.803631	-28.74775
8 to 9:	0.1834782	-4.738695	40.461304	-114.0730
9 - 10:	-0.25	7.25	-70	225
(NORMAL --> "x")	x^3	x^2	x	1

INTERMEDIATE OUTPUT

INTERVAL	STATION	NRMLIZD STATION RADIUS:
0 TO 1:	0:	0
	1:	2.105
1 TO 2:	1:	1.073979
	2:	1.984693
2 TO 3	2:	0.660441
	3:	1.019524
3 TO 4	3:	1.086877
	4:	1.131221
4 TO 5	4:	0.123542
	5:	0.123542
5 TO 6	5:	0.471698
	6:	0.450943
6 TO 7	6:	0.481660
	7:	0.412333
7 TO 8	7:	0.394371
	8:	0.249807
	8:	0.281739
	9:	0
	9:	0
	10:	0

INTERVAL	NRMLIZD SURF AREA
0 TO 1	17.15
1 TO 2	13.18
2 TO 3	6.188
3 TO 4	6.981
4 TO 5	0.776
5 TO 6	2.909
6 TO 7	2.852
7 TO 8	2.065
8 TO 9	0.981
9 TO 10	0.129
	53.22
	TOTAL NRMLIZD AREA

0 TO 1: matrix input: [F]

X0:	0		0	0	0	1
X1:	1	[F]=	1	1	1	1
			0	0	1	0
LOCAL INPUTS:			3	2	1	0
U0:	0					
U1:	2.105	DET [F] =		-1		
S0:	6					
S1:	1.3		2	-2	1	1
	[US]	[F]^-1	-3	3	-2	-1
LOCAL COEFFICIENTS:			0	0	1	0
a:	3.09		1	0	0	0
b:	-6.98					
c:	6					
d:	0					
	[C]					

SUB-	a	b	c	d	0 TO 1			
STATION	3.09	-6.98	6	0				
NUMBER:							AVG	SURF
"x"	x^3	x^2	x^1	x^0	U(x)	L(i)	RADIUS	AREA
0	0	0	0	1	0			
0.1	0.001	0.01	0.1	1	0.53324	0.542535	0.26662	0.908868
0.2	0.008	0.04	0.2	1	0.94532	0.424040	0.73928	1.969679
0.3	0.027	0.09	0.3	1	1.25478	0.325216	1.10005	2.247834
0.4	0.064	0.16	0.4	1	1.48016	0.246568	1.36747	2.118535
0.5	0.125	0.25	0.5	1	1.64	0.188543	1.56008	1.848159
0.6	0.216	0.36	0.6	1	1.75284	0.150774	1.69642	1.607090
0.7	0.343	0.49	0.7	1	1.83722	0.130843	1.79503	1.475717
0.8	0.512	0.64	0.8	1	1.91168	0.124676	1.87445	1.468382
0.9	0.729	0.81	0.9	1	1.99476	0.130008	1.95322	1.595525
1	1	1	1	1	2.105	0.148838	2.04988	1.917004
							TOTAL:	17.15679

---

1 TO 2: matrix input: [F]

X1:	1		1	1	1	1
X2:	2	[F]=	8	4	2	1
			3	2	1	0
LOCAL INPUTS:			12	4	1	0
U1:	1.073					
U2:	1.984	DET [F] =		-1		
S1:	1.3					
S2:	0.9		2	-2	1	1
		[F]^-1	-9	9	-5	-4
LOCAL COEFFICIENTS:			12	-12	8	5
a:	0.378		-4	5	-4	-2
b:	-1.90					
c:	3.971					
d:	-1.37					

SUB-STATION NUMBER: "x"	a 0.378 x^3	b -1.90 x^2	c 3.971 x^1	d -1.37 x^0	1 TO 2 U(x)	L(i)	AVG RADIUS	SURF AREA
1	1	1	1	1	1.073979			
1.1	1.331	1.21	1.1	1	1.196679	0.158288	1.135329	1.129149
1.2	1.728	1.44	1.2	1	1.306293	0.148375	1.251486	1.166724
1.3	2.197	1.69	1.3	1	1.405093	0.140575	1.355693	1.197431
1.4	2.744	1.96	1.4	1	1.495351	0.134708	1.450222	1.227465
1.5	3.375	2.25	1.5	1	1.579336	0.130589	1.537343	1.261417
1.6	4.096	2.56	1.6	1	1.659322	0.128053	1.619329	1.302887
1.7	4.913	2.89	1.7	1	1.737579	0.126981	1.698451	1.355101
1.8	5.832	3.24	1.8	1	1.816379	0.127316	1.776979	1.421498
1.9	6.859	3.61	1.9	1	1.897993	0.129077	1.857186	1.506206
2	8	4	2	1	1.984693	0.132351	1.941343	1.614398
							TOTAL:	13.18228

---

2 TO 3: matrix input: [F] (local)

X2:	2		8	4	2	1
X3:	3	[F]=	27	9	3	1
			12	4	1	0
LOCAL INPUTS:			27	6	1	0
U2:	0.660					
U3:	1.019	DET [F] =		-1		
S2:	0.9					
S3:	0.01		2	-2	1	1
		[F]^-1	-15	15	-8	-7
LOCAL COEFFICIENTS:			36	-36	21	16
a:	0.191		-27	28	-18	-12
b:	-1.88					
c:	6.133					
d:	-5.60					

SUB-	a	b	c	d	2 TO 3			
STATION	0.191	-1.88	6.133	-5.60				
NUMBER:							AVG	SURF
"x"	x^3	x^2	x^1	x^0	U(x)	L(i)	RADIUS	AREA
2	8	4	2	1	0.660441			
2.1	9.261	4.41	2.1	1	0.743305	0.129871	0.701873	0.572731
2.2	10.64	4.84	2.2	1	0.812666	0.121699	0.777985	0.594896
2.3	12.16	5.29	2.3	1	0.869673	0.115107	0.841169	0.608371
2.4	13.82	5.76	2.4	1	0.915478	0.109991	0.892576	0.616856
2.5	15.62	6.25	2.5	1	0.951233	0.106199	0.933355	0.622802
2.6	17.57	6.76	2.6	1	0.978087	0.103543	0.964660	0.627588
2.7	19.68	7.29	2.7	1	0.997192	0.101808	0.987639	0.631776
2.8	21.95	7.84	2.8	1	1.009699	0.100779	1.003446	0.635396
2.9	24.38	8.41	2.9	1	1.016760	0.100248	1.013230	0.638216
3	27	9	3	1	1.019524	0.100038	1.018142	0.639962
							TOTAL:	6.188598

3 TO 4: matrix input: [F] (local)

X3:	3		27	9	3	1
X4:	4	[F]=	64	16	4	1
			27	6	1	0
LOCAL INPUTS:			48	8	1	0
U3:	1.086					
U4:	1.131	DET [F] =		-1		
S3:	0.01					
S4:	0		2	-2	1	1
		[F]^-1	-21	21	-11	-10
LOCAL COEFFICIENTS:			72	-72	40	33
a:	-0.07		-80	81	-48	-36
b:	0.821					
c:	-2.79					
d:	4.198					

SUB-STATION NUMBER: "x"	a -0.07 x^3	b 0.821 x^2	c -2.79 x^1	d 4.198 x^0	3 TO 4 U(x)	L(i)	AVG RADIUS	SURF AREA
3	27	9	3	1	1.086877			
3.1	29.79	9.61	3.1	1	1.088929	0.100021	1.087903	0.683693
3.2	32.76	10.24	3.2	1	1.092769	0.100073	1.090849	0.685906
3.3	35.93	10.89	3.3	1	1.097926	0.100132	1.095347	0.689141
3.4	39.30	11.56	3.4	1	1.103926	0.100179	1.100926	0.692976
3.5	42.87	12.25	3.5	1	1.110299	0.100202	1.107113	0.697030
3.6	46.65	12.96	3.6	1	1.116572	0.100196	1.113436	0.700967
3.7	50.65	13.69	3.7	1	1.122273	0.100162	1.119423	0.704496
3.8	54.87	14.44	3.8	1	1.126929	0.100108	1.124601	0.707373
3.9	59.31	15.21	3.9	1	1.130070	0.100049	1.128500	0.709406
4	64	16	4	1	1.131221	0.100006	1.130645	0.710452
							TOTAL:	6.981447

4 TO 5: matrix input: [F] (local)

X4:	4		64	16	4	1
X5:	5	[F]=	125	25	5	1
			48	8	1	0
LOCAL INPUTS:			75	10	1	0
U4:	0.123					
U5:	0.123	DET [F] =		-1		
S4:	0					
S5:	0		2	-2	1	1
		[F]^-1	-27	27	-14	-13
LOCAL COEFFICIENTS:			120	-120	65	56
a:	0		-175	176	-100	-80
b:	0					
c:	0					
d:	0.123					

SUB-	a	b	c	d		4 TO 5		
STATION	0	0	0	0.123				
NUMBER:							AVG	SURF
"x"	x^3	x^2	x^1	x^0	U(x)	L(i)	RADIUS	AREA
4	64	16	4	1	0.123542			
4.1	68.92	16.81	4.1	1	0.123542	0.1	0.123542	0.077623
4.2	74.08	17.64	4.2	1	0.123542	0.1	0.123542	0.077623
4.3	79.50	18.49	4.3	1	0.123542	0.1	0.123542	0.077623
4.4	85.18	19.36	4.4	1	0.123542	0.1	0.123542	0.077623
4.5	91.12	20.25	4.5	1	0.123542	0.1	0.123542	0.077623
4.6	97.33	21.16	4.6	1	0.123542	0.1	0.123542	0.077623
4.7	103.8	22.09	4.7	1	0.123542	0.1	0.123542	0.077623
4.8	110.5	23.04	4.8	1	0.123542	0.1	0.123542	0.077623
4.9	117.6	24.01	4.9	1	0.123542	0.1	0.123542	0.077623
5	125	25	5	1	0.123542	0.1	0.123542	0.077623
							TOTAL:	0.776238

5 TO 6: matrix input: [F] (local)

X5:	5		125	25	5	1
X6:	6	[F]=	216	36	6	1
			75	10	1	0
LOCAL INPUTS:			108	12	1	0
U5:	0.471					
U6:	0.450	DET [F] =		-1		
S5:	0					
S6:	-0.02		2	-2	1	1
		[F]^-1	-33	33	-17	-16
LOCAL COEFFICIENTS:			180	-180	96	85
a:	0.021		-324	325	-180	-150
b:	-0.36					
c:	2.035					
d:	-3.27					

SUB-STATION NUMBER: "x"	a 0.021 x^3	b -0.36 x^2	c 2.035 x^1	d -3.27 x^0	5 TO 6 U(x)	L(i)	AVG RADIUS	SURF AREA
5	125	25	5	1	0.471698			
5.1	132.6	26.01	5.1	1	0.471296	0.100000	0.471497	0.296253
5.2	140.6	27.04	5.2	1	0.470179	0.100006	0.470738	0.295792
5.3	148.8	28.09	5.3	1	0.468475	0.100014	0.469327	0.294929
5.4	157.4	29.16	5.4	1	0.466312	0.100023	0.467393	0.293740
5.5	166.3	30.25	5.5	1	0.463820	0.100031	0.465066	0.292300
5.6	175.6	31.36	5.6	1	0.461129	0.100036	0.462474	0.290686
5.7	185.1	32.49	5.7	1	0.458366	0.100038	0.459747	0.288978
5.8	195.1	33.64	5.8	1	0.455661	0.100036	0.457014	0.287255
5.9	205.3	34.81	5.9	1	0.453144	0.100031	0.454403	0.285600
6	216	36	6	1	0.450943	0.100024	0.452043	0.284096
							TOTAL:	2.909633

---

6 TO 7: matrix input: [F] (local)

X6:	6		216	36	6	1
X7:	7	[F]=	343	49	7	1
			108	12	1	0
LOCAL INPUTS:			147	14	1	0
U6:	0.481					
U7:	0.412	DET [F] =		-1		
S6:	-0.02					
S7:	-0.09		2	-2	1	1
		[F]^-1	-39	39	-20	-19
LOCAL COEFFICIENTS:			252	-252	133	120
a:	0.028		-539	540	-294	-252
b:	-0.59					
c:	4.010					
d:	-8.39					

SUB-STATION NUMBER: "x"	a 0.028 x^3	b -0.59 x^2	c 4.010 x^1	d -8.39 x^0	6 TO 7 U(x)	L(i)	AVG RADIUS	SURF AREA
6	216	36	6	1	0.481660			
6.1	226.9	37.21	6.1	1	0.478909	0.100037	0.480285	0.301886
6.2	238.3	38.44	6.2	1	0.474770	0.100085	0.476840	0.299863
6.3	250.0	39.69	6.3	1	0.469416	0.100143	0.472093	0.297049
6.4	262.1	40.96	6.4	1	0.463017	0.100204	0.466216	0.293531
6.5	274.6	42.25	6.5	1	0.455747	0.100263	0.459382	0.289400
6.6	287.4	43.56	6.6	1	0.447776	0.100317	0.451761	0.284750
6.7	300.7	44.89	6.7	1	0.439278	0.100360	0.443527	0.279681
6.8	314.4	46.24	6.8	1	0.430423	0.100391	0.434851	0.274293
6.9	328.5	47.61	6.9	1	0.421384	0.100407	0.425904	0.268694
7	343	49	7	1	0.412333	0.100408	0.416859	0.262991
							TOTAL:	2.852143

---

7 TO 8: matrix input: [F] (local)

X7:	7		343	49	7	1
X8:	8	[F]=	512	64	8	1
			147	14	1	0
LOCAL INPUTS:			192	16	1	0
U7:	0.394					
U8:	0.249	DET [F] =		-1		
S7:	-0.09					
S8:	-0.13		2	-2	1	1
		[F]^-1	-45	45	-23	-22
LOCAL COEFFICIENTS:			336	-336	176	161
a:	0.069		-832	833	-448	-392
b:	-1.57					
c:	11.80					
d:	-28.7					

SUB-	a	b	c	d	7 TO 8			
STATION	0.069	-1.57	11.80	-28.7				
NUMBER:							AVG	SURF
"x"	x^3	x^2	x^1	x^0	U(x)	L(i)	RADIUS	AREA
7	343	49	7	1	0.394371			
7.1	357.9	50.41	7.1	1	0.384203	0.100515	0.389287	0.245857
7.2	373.2	51.84	7.2	1	0.371976	0.100744	0.378090	0.239330
7.3	389.0	53.29	7.3	1	0.358105	0.100957	0.365041	0.231558
7.4	405.2	54.76	7.4	1	0.343004	0.101133	0.350555	0.222757
7.5	421.8	56.25	7.5	1	0.327089	0.101258	0.335047	0.213165
7.6	438.9	57.76	7.6	1	0.310773	0.101322	0.318931	0.203040
7.7	456.5	59.29	7.7	1	0.294473	0.101319	0.302623	0.192653
7.8	474.5	60.84	7.8	1	0.278601	0.101251	0.286537	0.182290
7.9	493.0	62.41	7.9	1	0.263575	0.101122	0.271088	0.172242
8	512	64	8	1	0.249807	0.100943	0.256691	0.162805
							TOTAL:	2.065701

8 TO 9: matrix input: [F] (local)

X8:	8		512	64	8	1
X9:	9	[F]=	729	81	9	1
			192	16	1	0
LOCAL INPUTS:			243	18	1	0
U8:	0.281					
U9:	0	DET [F] =		-1		
S8:	-0.13					
S9:	-0.25		2	-2	1	1
		[F]^-1	-51	51	-26	-25
LOCAL COEFFICIENTS:			432	-432	225	208
a:	0.183		-1215	1216	-648	-576
b:	-4.73					
c:	40.46					
d:	-114.					

SUB-	a	b	c	d	8 TO 9			
STATION	0.183	-4.73	40.46	-114.				
NUMBER:							AVG	SURF
"x"	x^3	x^2	x^1	x^0	U(x)	L(i)	RADIUS	AREA
8	512	64	8	1	0.281739			
8.1	531.4	65.61	8.1	1	0.265570	0.101298	0.273654	0.174175
8.2	551.3	67.24	8.2	1	0.243798	0.102342	0.254684	0.163771
8.3	571.7	68.89	8.3	1	0.217523	0.103394	0.230660	0.149847
8.4	592.7	70.56	8.4	1	0.187846	0.104310	0.202685	0.132840
8.5	614.1	72.25	8.5	1	0.155869	0.104988	0.171858	0.113368
8.6	636.0	73.96	8.6	1	0.122692	0.105360	0.139280	0.092203
8.7	658.5	75.69	8.7	1	0.089415	0.105391	0.106053	0.070228
8.8	681.4	77.44	8.8	1	0.057140	0.105079	0.073278	0.048380
8.9	704.9	79.21	8.9	1	0.026968	0.104452	0.042054	0.027600
9	729	81	9	1	1.0E-15	0.103572	0.013484	0.008775
							TOTAL:	0.981191

9 TO 10: matrix input: [F] (local)

X9:	9		729	81	9	1
X10:	10	[F]=	1000	100	10	1
			243	18	1	0
LOCAL INPUTS:			300	20	1	0
U9:	0					
U10:	0	DET [F] =		-1		
S9:	-0.25					
S10:	0		2	-2	1	1
		[F]^-1	-57	57	-29	-28
LOCAL COEFFICIENTS:			540	-540	280	261
a:	-0.25		-1700	1701	-900	-810
b:	7.25					
c:	-70					
d:	225					

SUB-STATION NUMBER: "x"	a -0.25 x^3	b 7.25 x^2	c -70 x^1	d 225 x^0	9 TO 10 U(x)	L(i)	AVG RADIUS	SURF AREA
9	729	81	9	1	0			
9.1	753.5	82.81	9.1	1	-0.02025	0.102029	0.010125	0.006490
9.2	778.6	84.64	9.2	1	-0.032	0.100687	0.026125	0.016527
9.3	804.3	86.49	9.3	1	-0.03675	0.100112	0.034375	0.021622
9.4	830.5	88.36	9.4	1	-0.036	0.100002	0.036375	0.022855
9.5	857.3	90.25	9.5	1	-0.03125	0.100112	0.033625	0.021151
9.6	884.7	92.16	9.6	1	-0.024	0.100262	0.027625	0.017402
9.7	912.6	94.09	9.7	1	-0.01575	0.100339	0.019875	0.012530
9.8	941.1	96.04	9.8	1	-0.008	0.100299	0.011875	0.007483
9.9	970.2	98.01	9.9	1	-0.00225	0.100165	0.005125	0.003225
10	1000	100	10	1	0	0.100025	0.001125	0.000707
							TOTAL:	0.129997

APPENDIX C: CALCULATION OF SHAFT HORSEPOWER WHILE SUBMERGED

Essential to the calculation of endurance range and indiscretion rate is the calculation of shaft horsepower (SHP) required to make a given speed. The following formulas are taken from Reference (16), and is used to determine the required SHP at various speeds in submerged operating mode.

SHP = EHP/PC EQN C-1

EHP = 0.00872 (V^3) * [WS*(Cf+Ca+Cr) + (Ss*Cds) + (Sa*Cda)] EQN C-2

where:

SHP = Shaft Horsepower required at the transit speed, operations well-submerged, HP.
EHP = Effective Horsepower, HP.
PC = Propulsive Coefficient;

PC assumed to be 0.8.

V = Speed (Submerged), Kts.
WS = Wetted Surface Area of Bare Hull, sq ft.
Sa = Wetted Surface of Appendages, sq ft.
Ss = Wetted Surface of Sail, sq ft.
Cf = Coefficient of Frictional Resistance;

Cf = 0.075 / [(log10(Re#)-2)^2].

Re# = Reynold's Number.
Ca = Correlation Allowance;

Ca = 0.0004.

Cr = Coefficient of Form Resistance;

Cr = Cf*[1.5(D/L)^1.5 + 7(D/L)^3 + 0.002(Cp-0.6)].

Cp = Prismatic Coefficient.
Cds = Coefficient of Drag, Sail;

Cds = 0.0090.

Cda = Coefficient of Drag, Appendages;

Cda = 0.0060.

Table C1 lists the values of required SHP for each of the submarines, for speed ranges of which each is capable.

REQUIRED SHP SUBMERGED TRANSITS	KILO HP	WALRUS HP	RUBIS HP	BARBEL HP	TYPE 2400
2	6.531857	6.392620	6.069771	5.365803	6.029493
2.5	12.51668	12.26146	11.63246	10.27074	11.56157
3	21.30373	20.88531	19.80046	17.46533	19.68849
3.5	33.40885	32.77371	31.05360	27.36876	30.88945
4	49.34248	48.43113	45.86670	40.39554	45.63881
4.25	58.90326	57.82973	54.75547	48.20864	54.49127
4.5	69.61058	68.35792	64.71045	56.95628	64.40695
4.75	81.52711	80.07769	75.78993	66.68930	75.44411
5	94.71529	93.05085	88.05200	77.45831	87.66084
5.25	109.2373	107.3390	101.5545	89.31378	101.1150
5.5	125.1554	123.0036	116.3554	102.3060	115.8644
6	161.4269	158.7072	150.0821	131.9013	149.4793
6.5	204.0230	200.6502	189.6910	166.6439	188.9644
7	253.4347	249.3190	235.6389	206.9313	234.7767
7.5	310.1508	305.1979	288.3806	253.1592	287.3713
8	374.6580	368.7695	348.3692	305.7217	347.2015
8.5	447.4415	440.5147	416.0558	365.0112	414.7190
9	528.9845	520.9128	491.8903	431.4188	490.3740
10	720.2750	709.5777	669.7949	587.1454	667.8907
11	952.3668	938.5714	885.6538	776.0041	883.3268
12	1229.076	1211.681	1143.018	1001.079	1140.239
13	1554.202	1532.680	1445.424	1265.439	1442.168
14	1931.526	1905.321	1796.389	1572.139	1792.640
15	2364.813	2333.346	2199.419	1924.219	2195.167
16	2857.817	2820.483	2658.007	2324.708	2653.248
17	3414.277	3370.449	3175.632	2776.624	3170.371
18	4037.921	3986.949	3755.764	3282.974	3750.015
19	4732.466	4673.679	4401.863	3846.757	4395.646
20	5501.617	5434.322	5117.377	4470.960	5110.724
21	6349.071	6272.557	5905.747	5158.565	5898.698
22	7278.516	7192.050	6770.407	5912.545	6763.011
23	8293.630	8196.462	7714.778	6735.863	7707.095
24	9398.085	9289.445	8742.279	7631.478	8734.378
25	10595.54	10474.64	9856.318	8602.342	9848.279

LITERATURE/MODEL CORRELATION	KILO	WALRUS	RUBIS	BARBEL	TYPE 2400
ADVERTISED SHP	4000	?	10000	3150	5400
PREDICTED SPEED	18	*	25.1	17.8	20.5
ADVERTISED SPEED	25	20	25	21	20
PREDICTED SHP	10596	5434	9856	5159	5110
LITERATURE/MODEL CORRELATION:	UNSAT	N/A	SAT	UNSAT	SAT

TABLE C1: Calculated values of required shaft horsepower (SHP) as a function of speed. The lower part of the table indicates the correlation of the calculated data with that found in the literature. (Sheet one of two).

REQUIRED SHP SUBMERGED TRANSITS	TYPE 1700 HP	TYPE 2000 HP	SAURO HP	VASTER-GOTLAND HP	MIDGET 100
2	5.662832	4.733628	4.289857	3.103136	0.849841
2.5	10.84755	9.047344	8.212617	5.927847	1.622428
3	18.45759	15.36660	13.96739	10.06407	2.753222
3.5	28.93865	24.05591	21.88989	15.74966	4.307059
4	42.73170	35.47532	32.31210	23.21952	6.347967
4.25	51.00693	42.32031	38.56350	27.69627	7.570894
4.5	60.27376	49.98122	45.56295	32.70609	8.939301
4.75	70.58630	58.50212	53.35116	38.27772	10.46102
5	81.99847	67.92690	61.96871	44.43978	12.14385
5.25	94.56402	78.29930	71.45603	51.22079	13.99556
5.5	108.3365	89.66289	81.85342	58.64916	16.02390
6	139.7161	115.5373	105.5390	75.56124	20.64133
6.5	176.5632	145.8963	133.3458	95.40158	26.05759
7	219.3013	181.0838	165.5924	118.3944	32.33380
7.5	268.3526	221.4422	202.5958	144.7630	39.53078
8	324.1371	267.3123	244.6719	174.7294	47.70902
8.5	387.0734	319.0333	292.1352	208.5147	56.92878
9	457.5786	376.9430	345.2991	246.3389	67.25004
10	622.9573	512.6739	469.9769	334.9811	91.43592
11	823.5842	677.1839	621.1921	442.4015	120.7422
12	1062.751	873.1349	801.4175	570.3344	155.6416
13	1343.736	1103.173	1013.113	720.5039	196.6037
14	1669.800	1369.933	1258.727	894.6254	244.0960
15	2044.190	1676.035	1540.698	1094.405	298.5836
16	2470.145	2024.088	1861.454	1321.544	360.5296
17	2950.887	2416.691	2223.416	1577.734	430.3950
18	3489.632	2856.433	2628.995	1864.661	508.6395
19	4089.584	3345.894	3080.594	2184.005	595.7206
20	4753.938	3887.647	3580.612	2537.441	692.0948
21	5485.882	4484.254	4131.437	2926.637	798.2169
22	6288.595	5138.271	4735.455	3353.259	914.5404
23	7165.247	5852.249	5395.043	3818.966	1041.517
24	8119.004	6628.729	6112.574	4325.414	1179.599
25	9153.021	7470.247	6890.414	4874.252	1329.235

LITERATURE/MODEL CORRELATION	TYPE 1700	TYPE 2000	SAURO	VASTER-GOTLAND	MIDGET 100
ADVERTIZED SHP	8844	7500	3216	?	420
PREDICTED SPEED	24.7	25	19.3	*	16.8
ADVERTIZED SPEED	25	25	19.3	20	1[illegible]
PREDICTED SHP	9153	7470	3228	2537	5[illegible]
LITERATURE/MODEL CORRELATION:	SAT	SAT	SAT	N/A	UNSAT

TABLE II: Calculated values of required shaft horsepower (SHP) as a function of speed. The lower part of the table indicates the correlation of the calculated data with that found in the literature. (Sheet two of two.)

Copy available to DTIC does not permit fully legible reproduction

APPENDIX D: CALCULATION OF ADDED RESISTANCE AND REQUIRED SHAFT HORSEPOWER WHILE SNORKELING

When the submarine operates near the free surface of the ocean, it generates gravity waves. Generating the gravity waves requires power, which must be supplied by the submarine if it is to remain at the same speed as it had when transiting more deeply submerged. The power increase is not great, unless the submarine is operating at Froude numbers greater than about 0.6, or submergence depth less than one tenth of its length. Reference (16) lists a chart and provides a methodology for determining the added resistance coefficient due to operating close to the surface, Cw, as a function of Froude number, length-to-diameter ratio, and submergence ratio (operating depth divided by overall length). The calculations for the computation of Cw are as follows:

(1). Enter chart with submergence ratio and Froude number.

(2). $$Cw = \frac{(Ch\#)}{4[(L/D)-1.3606]*(L/D)^2} \qquad \text{EQN D-1}$$

(3). $$SHPw = 0.00872(V^3)(WS)(Cw) \qquad \text{EQN D-2}$$

where:

- Cw = Coefficient resistance due gravity wave generation.
- (L/D) = Length-to-Diameter ratio.
- SHPw = The additional shaft horsepower required due to the operation of the submarine near the surface.
- h/L = Submergence ratio: "h" is the depth of the submarine axis below the mean surface position; "L" is length overall.
- Ch# = The number obtained from chart, Reference (16).

The results of the calculations for each of the submarines are as listed in Table D1.

REQUIRED SHP SNORKELING	KILO	WALRUS	RUBIS	BARBEL	TYPE 2400
2	6.627676	6.475601	N/A	5.455644	6.089220
2.5	12.71367	12.43206	N/A	10.45545	11.68436
3	21.67818	21.20959	N/A	17.81642	19.92190
3.5	34.05752	33.33546	N/A	27.97696	31.29379
4	50.47214	49.40943	N/A	41.45472	46.34296
4.25	60.35502	59.08698	N/A	49.56983	55.39620
4.5	71.44879	69.94983	N/A	58.67981	65.55276
4.75	83.95927	82.18397	N/A	68.96971	76.96015
5	98.02483	95.91696	N/A	80.56136	89.72378
5.25	113.5246	111.0518	N/A	93.33360	103.7874
5.5	130.6092	127.7267	N/A	107.4195	119.2640
6	170.1414	166.2541	N/A	140.0721	154.9113
6.5	218.5651	213.2439	N/A	180.2787	198.0289
7	276.7868	269.5422	N/A	228.8264	249.3328
7.5	343.1280	333.7566	N/A	284.0789	307.9270
8	420.4898	408.4604	N/A	348.6940	375.7698
8.5	510.1577	494.8278	N/A	423.8146	453.8120
9	613.5423	594.1409	N/A	510.7010	543.0815
10	884.1761	851.5181	N/A	740.8206	770.0552
11	N/A	1156.559	N/A	N/A	N/A
12	N/A	1551.290	N/A	N/A	N/A
13	N/A	N/A	N/A	N/A	N/A
14	N/A	N/A	N/A	N/A	N/A
15	N/A	N/A	N/A	N/A	N/A

Table D1: The calculated values of required shaft horsepower when operating at snorkel depth. (Sheet one of two).

REQUIRED SHP SNORKELING	TYPE 1700	TYPE 2000	SAURO	VASTER-GOTLAND	MIDGET 100
2	5.725325	4.798516	4.335458	3.160754	N/A
2.5	10.97603	9.180750	8.306371	6.046307	N/A
3	18.70180	15.62018	14.14560	10.28924	N/A
3.5	29.36171	24.49518	22.19860	16.13973	N/A
4	43.46846	36.24032	32.84972	23.89881	N/A
4.25	51.95376	43.30344	39.25441	28.56926	N/A
4.5	61.47263	51.22606	46.43778	33.81147	N/A
4.75	72.17254	60.14917	54.50866	39.74025	N/A
5	84.15693	70.16811	63.54377	46.42991	N/A
5.25	97.36018	81.20264	73.49642	53.79887	N/A
5.5	111.8935	93.35619	84.44896	61.92870	N/A
6	145.3997	121.4387	109.6864	80.80153	N/A
6.5	186.0475	155.7441	140.2666	104.1462	N/A
7	234.5315	196.8978	176.7060	132.4368	N/A
7.5	289.8602	243.7743	218.2902	164.5932	N/A
8	354.0284	298.3494	266.4839	202.2895	N/A
8.5	427.9766	361.5045	321.9828	246.2278	N/A
9	512.7268	434.2053	385.5414	297.1861	N/A
10	729.8528	623.6671	547.9798	433.5398	N/A
11	987.7510	847.6439	740.9866	N/A	N/A
12	1318.511	1138.699	N/A	N/A	N/A
13	1723.108	1497.088	N/A	N/A	N/A
14	2166.189	1885.352	N/A	N/A	N/A
15	2626.976	2281.162	N/A	N/A	N/A

Table D1: The calculated values of required shaft horsepower when operating at snorkel depth. (Sheet two of two).

APPENDIX E: CALCULATION OF ENDURANCE RANGE

The fuel endurance range is calculated at the snorkel depth, and depends upon the following factors:

(1) Diesel engine specific fuel consumption.
(2) Bunker fuel load.
(3) Transit speed.
(4) Speed vs Power relation.
(5) Hotel electric load.
(6) Complement.
(7) Water temperature, (affects heating and/or A/C load).
(8) Sea State, (to the extent that it affects snorting).

All of these factors may play a part in determining the endurance range of the diesel-electric submarines, but only items (1) through (5) above can be estimated with a degree of accuracy given the data available in the literature.

It should be noted that in the matter of endurance range, "bigger is better". The reason for this economy of scale is that the drag force on a submerged body is proportional to its wetted surface area, but the fuel capacity is proportional to its internal volume.

The following relation, adapted from Reference (3), may be used to calculate endurance range:

$$Rf = 2240[(F)(0.8)(Nem)(V)]/[(SFC)(SHP + 1.34*Lh)] \qquad \text{EQN E-1}$$

where:

Rf = Endurance Range based on fuel, Nm.
F = Bunker fuel load, Ltons.
Nem = Efficiency of electro-mechanical energy conversion;

Nem is assumed to be 0.95.

V = Speed (submerged), Kts.
SFC = Diesel specific fuel consumption, lbs/HP-Hr;

SFC values are estimated in Appendix F.

SHP = Shaft horsepower, HP.
Lh = Hotel electric load, KW;

Lh values are estimated in Appendix M.

2240 = Conversion factor, (lbs/Lton).
0.8 = Proportion of bunker fuel consumed.
1.34 = Conversion factor, (HP/KW).

Table E-1 lists the fuel endurance range, calculated at snorkel depth.

"It may be mathematically proven that the maximum endurance range occurs at the speed for which the shaft horsepower required is exactly half of the hotel electric power requirement, (for a constant hotel power load)."

- Harry Jackson, P.E., CAPT USN, (Ret.)
24 April, 1988

The following is one way of proving CAPT Jackson's statement:

$$Pt = (SHP) + (Lh). \qquad \text{EQN E-2}$$

where:

Pt = Total power required at a given speed, HP.
SHP = Shaft Horsepower required at a given speed, HP.
Lh = Hotel electric load, assumed constant, HP.

Equation E-2 quantifies the power required at a given speed. The SHP is a function of speed, as shown by Equations C-1 and C-2, and can be approximated by the following expression:

$$SHP = (Kv)(V^3) \qquad \text{EQN E-3}$$

where:

Kv = A constant, determined from EQN C-1 and C-2.

Equation E-3 is suitably accurate within a suitable neighborhood of the point of evaluation of Kv. The maximum endurance range will occur at the speed for which the energy expenditure per mile is the least. The energy per mile is related to the power output by this expression:

$$E/Nm = Pt/V = (Kv)(V^2) + (Lh)/V \qquad \text{EQN E-4}$$

where:

E = Total Energy required by the ship at some speed, HP-Hour.
Nm = Nautical miles.

The energy per nautical mile will have a minima where its slope is zero, a point which may be found by:

$$(E/Nm) = 2(Kv)V - (Lh)/(V^2) = 0. \qquad \text{EQN E-5}$$

Rearranging Equation E-5:

$$Lh = 2(Kv)(V^3) = 2(SHP). \qquad \text{EQN E-6}$$

Which was to be proved.

FUEL RANGE (SNORKELING)	KILO	WALRUS	RUBIS	BARBEL	TYPE 2400
BUNKER FUEL, Lton	270	275	19.4	130	186.7
MECH/ELEC EFFCNCY	0.95	0.95	0.95	0.95	0.95
HOTEL LOAD, Kw	131.32	124.7981	129.784	94.38	115.94
FUEL USED, %	80	80	100	80	80
SPEED, Kts	ENDURANCE RANGE, Nm				
2	6828.326	7376.931	765.1887	4612.769	5438.270
2.5	8270.424	8929.778	935.3956	5566.245	6563.041
3	9491.796	10240.78	1088.135	6356.902	7550.171
3.5	10447.52	11261.99	1220.110	6955.936	8304.977
4	11111.65	11967.48	1329.747	7349.901	8829.774
4.25	11335.22	12203.45	1376.587	7472.756	9007.278
4.5	11489.80	12365.61	1418.630	7549.660	9131.270
4.75	11573.55	12452.93	1455.785	7579.379	9202.018
5	11589.68	12469.40	1488.519	7564.702	9222.793
5.25	11553.28	12430.53	1518.732	7517.778	9203.553
5.5	11467.88	12340.61	1547.090	7441.110	9147.898
6	11168.16	12028.46	1601.826	7211.156	8943.752
6.5	10712.26	11559.82	1659.270	6888.048	8634.084
7	10162.06	10998.98	1735.200	6515.530	8262.832
7.5	9616.423	10445.07		6164.247	7893.334
8	9057.255	9882.734		5815.509	7521.103
8.5	8505.609	9333.846		5481.798	7162.206
9	7976.095	8813.627		5171.633	6828.157
10	6909.486	7786.273		4560.516	6196.245
11		7145.193			
12		6673.183			
13					
14					
15					

TABLE E1: Calculated values of endurance range based upon bunker fuel loadout, at snorkel depth. For RUBIS, values reflect range on emrgency diesel. (Sheet one of two).

FUEL RANGE (SNORKELING)	TYPE 1700	TYPE 2000	SAURO	VASTER-GOTL'D	MIDGET 100
BUNKER FUEL, Lton	319	236	144	40	4
MECH/ELEC EFFCNCY	0.95	0.95	0.95	0.95	0.95
HOTEL LOAD, Kw	114.996	108.2	88.137	63.882	15
FUEL USED, %	80	80	80	80	80
SPEED, Kts		ENDURANCE	RANGE, Nm		
2	9499.596	7579.153	5665.119	2088.014	875.6985
2.5	11522.91	9226.273	6877.205	2531.192	1055.691
3	13253.47	10664.33	7919.184	2908.679	1204.146
3.5	14631.38	11846.46	8755.996	3206.897	1315.400
4	15622.82	12741.29	9367.636	3417.363	1387.308
4.25	15974.44	13079.28	9589.354	3489.808	1408.870
4.5	16234.37	13346.19	9757.475	3541.290	1421.450
4.75	16401.71	13539.13	9871.493	3570.673	1425.709
5	16481.18	13660.13	9934.110	3578.675	1422.422
5.25	16490.35	13723.52	9955.493	3570.548	1412.429
5.5	16434.69	13732.24	9938.861	3547.081	1396.604
6	16155.11	13602.10	9807.015	3458.826	1350.894
6.5	15678.34	13287.93	9559.896	3318.002	1291.741
7	15082.63	12853.73	9243.734	3145.032	1224.593
7.5	14488.89	12412.32	8930.694	2975.464	1153.708
8	13885.91	11947.53	8615.637	2800.381	1082.200
8.5	13304.94	11487.99	8318.752	2626.659	1012.211
9	12769.76	11056.54	8056.444	2459.172	945.1152
10	11764.03	10200.01	7602.278	2113.869	822.4142
11	11337.42	9912.255	7622.481		716.4156
12	10850.59	9321.353			626.3427
13	9454.215	7670.309			550.2781
14	6627.458	5355.612			486.0792
15	4775.783	3911.715			431.7544

TABLE E1: Calculated values of endurance range based upon bunker fuel loadout, at snorkel depth. MIDGET 100 calculated at deep submerged depth. (Sheet two of two).

APPENDIX F: LEAD-ACID BATTERY POWER AND ENERGY CHARACTERISTICS

F.1. Type of Battery

It is commonly held that the type of secondary storage batteries in modern diesel-electric submarines are of the lead-acid variety, although the literature did not confirm this. Some of the reasons for the popularity of lead-acid cells in submarines are as follows, from Reference (20):

(1) Lowest cost (by a factor of ten) per KW-Hr of all storage batteries.
(2) Reasonably high power to volume density.
(3) The weight is beneficial to stability.
(4) Maintainance is available throughout the world.
(5) Good safety record.

Reasons for the popularity of lead-acid batteries in submarine propulsion.

F.2. Power and Energy Capacity

The energy available from a lead-acid cell is dependent upon the rate of energy extraction - the power demanded of the cell relative to the cell's capacity. This is because the internal electrical resistance of the lead plates and the internal fluid resistance of the ions in the acid electrolyte both increase with increasing power demands. This effect has been minimised in state-of-the-art batteries manufactured by such firms as Varta and Hagen of West Germany, and Gould of the U.S. Below are listed the most important factors concerning the battery capacity are, from Reference (20):

(1) Battery nominal energy capacity.
(2) Battery design, (geometry and structure).
(3) Maintainance state of the battery.
(4) Number of previous deep-discharge cycles on the battery.
(5) Battery internal resistance.
(6) Battery power vs energy relation.
(7) Temperature of discharge.

Factors contributing to battery capacity.

For a typical lead-acid storage cell of the type used in submarines, the total energy capacity, when discharged at the 100-hour rate, is approximately 23.5 KW-Hrs, calculated from Reference (16). The available energy capacity of the battery is reduced for faster discharge rates. A numerical curve-fit describing the energy capacity of this typical cell, as a function of service-life, may be descibed by a sum of first-order transients, given by Equation F-1.

$$Ec = (23KW\text{-}Hrs)*[0.3030(1-\exp(-Td/26))+ 0.2597(1-\exp(-Td/2.7))+ 0.2424(1-\exp(-Td/0.41))+ 0.1948(1-\exp(-Td/0.05))] \quad \text{EQN F-1}$$

where:

- Ec = The energy in a single cell, KW-Hrs.
- Eb = The energy in the entire battery, KW-Hrs.
- Td = Service life, Hrs. The time required to discharge the battery to a given end-voltage at a given discharge rate.
- #C = The number of standard cells in the battery.

Table F1 gives the calculated values of battery energy capacity for each of the submarines, at discharge rates equal to that necessary to maintain the corresponding speed. Figure F-1 graphically displays the information of Table F1.

F.3. Other Factors

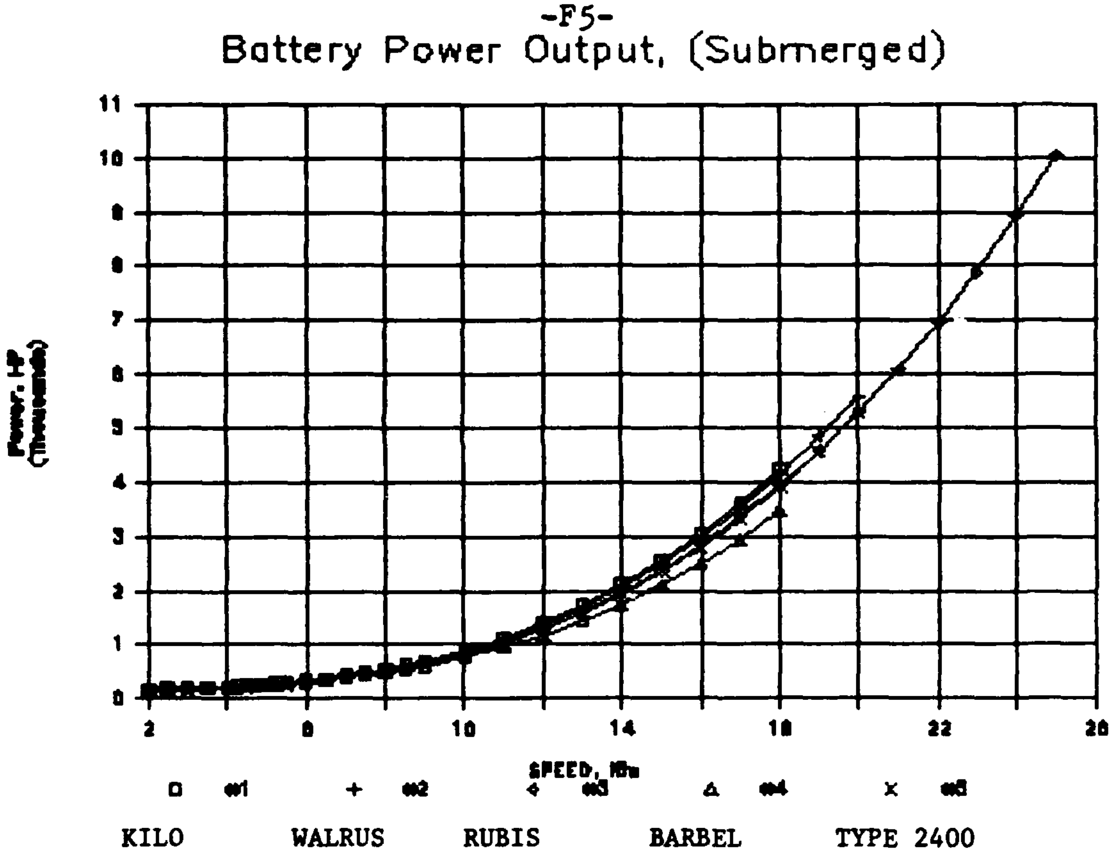
A well-designed battery will minimize internal resistance and allow more complete energy utilization at high discharge rates. One way of reducing the internal resistance is to use sandwich anode and cathode plates, which have internal cores of copper which is about fifteen times more conductive than lead at room temperature, References (20) and (22). This decreased resistance is very important in reducing the ampere heating of the lead plates at high discharge currents. The battery may also be provided with its own cooling system to prevent overheating. The battery room should also be equipped with a separate ventilation system, to safely duct away any evolved hydrogen during charging periods.

AVAILABLE BATTERY ENERGY	KILO	WALRUS	RUBIS	BARBEL	TYPE 2400
BATTERY ENERGY @ 100 Hr Rate	KW-Hrs 11280	KW-Hrs 11280	N/A	KW-Hrs 11344	KW-Hrs 11280
HOTEL LOAD, Kw	131.32	124.7981	129.784	94.382	115.94
DISCHARGE DEPTH	0.80	0.80	0.80	0.80	0.80
SPEED, Kts	AVAILABLE BATTERY ENERGY, KW-Hrs 80% Depth of Discharge				
2	8795.195	8824.135	N/A	9401.776	8861.980
2.5	8775.106	8805.127	N/A	9391.190	8845.186
3	8744.907	8776.362	N/A	9374.460	8819.562
3.5	8702.218	8735.374	N/A	9349.264	8782.661
4	8644.727	8679.683	N/A	9312.742	8731.883
4.25	8609.823	8645.642	N/A	9289.242	8700.524
4.5	8570.593	8607.202	N/A	9261.723	8664.851
4.75	8526.963	8564.257	N/A	9229.821	8624.693
5	8478.956	8516.792	N/A	9193.233	8579.966
5.25	8426.695	8464.901	N/A	9151.734	8530.688
5.5	8370.410	8408.790	N/A	9105.202	8476.991
6	8247.203	8285.287	N/A	8997.166	8357.441
6.5	8113.035	8149.961	N/A	8870.695	8224.562
7	7972.445	8007.481	N/A	8729.329	8082.845
7.5	7829.967	7862.627	N/A	8578.008	7937.212
8	7689.299	7719.408	N/A	8422.166	7792.098
8.5	7552.719	7580.411	N/A	8266.781	7650.718
9	7420.914	7446.564	N/A	8115.609	7514.674
10	7167.943	7191.117	N/A	7832.737	7257.468
11	6917.337	6940.028	N/A	7572.6[illegible]	7009.395
12	6657.415	6680.689	N/A	7321.232	6756.526
13	6386.219	6410.077	N/A	7065.208	6492.863
14	6111.165	6134.921	N/A	6799.922	6222.40[illegible]
15	5843.308	5866.184	N/A	6527.524	5955.008
16	5590.706	5612.322	N/A	6262.[illegible]03	5700.031
17	5354.931	5379.450	N/A	6003.[illegible]	5461.[illegible]
18	5131.988	5151.930	N/A	5769.706	5237.965
19		4935.503	N/A		[illegible]
20		4720.241	N/A		48[illegible]
21			N/A		
22			N/A		
23			N/A		
24			N/A		
25			N/A		

TABLE F1. Available energy [illegible] submarine batte[illegible] sit speeds, 80% depth [illegible] discharge. (Page [illegible]

SUBMARINE NAME					
AVAILABLE BATTERY ENERGY	TYPE 1700	TYPE 2000	SAURO	VASTER-GOTL'D	MIDGET 100
BATTERY ENERGY @ 100 Hr Rate	KW-Hrs 22560	KW-Hrs 16920	KW-Hrs 6956	KW-Hrs 3948	KW-Hrs 352.5
HOTEL LOAD, Kw	114.996	108.2	88.137	63.882	15
DISCHARGE DEPTH	0.80	0.80	0.80	0.80	0.80
SPEED, Kts	AVAILABLE BATTERY ENERGY, KW-Hrs 80% Depth of Discharge				
2	18030.45	13495.65	5389.971	2989.427	233.5459
2.5	18027.16	13490.10	5376.162	2979.089	232.3389
3	18021.60	13481.19	5355.592	2964.042	230.6581
3.5	18012.44	13467.48	5326.847	2943.625	228.4918
4	17997.61	13446.91	5288.653	2917.437	225.8517
4.25	17987.17	13433.25	5265.713	2902.156	224.3604
4.5	17974.09	13416.83	5240.126	2885.46[illegible]	222.7579
4.75	17957.82	13397.21	5211.893	2867.434	221.0456
5	17937.76	13373.97	5181.070	2848.174	219.2238
5.25	17913.24	13346.65	5147.779	2827.819	217.2922
5.5	17883.57	13314.80	5112.201	2806.526	215.2501
6	17806.06	13235.94	5035.190	2761.832	210.8330
6.5	17700.19	13134.83	4952.456	2715.515	205.9839
7	17562.39	13010.35	4866.744	2668.821	200.7491
7.5	17391.42	12863.21	4780.601	2622.575	195.2198
8	17188.89	12696.05	4695.922	2577.074	189.5238
8.5	16959.13	12513.14	4613.680	2532.127	183.8000
9	16708.63	12319.75	4533.911	2487.219	178.1664
10	16176.10	11923.23	4378.615	2395.095	167.3933
11	15648.13	11542.15	4221.627	2297.458	157.1399
12	15159.23	11192.34	4057.175	2195.212	146.8957
13	14714.75	10869.87	3886.142	2092.662	136.3115
14	14299.97	10560.70	3714.622	1994.420	125.5231
15	13894.78	10251.05	3549.555	1902.641	115.0389
16	13484.28	9933.378	3394.779	1816.432	105.3599
17	13063.01	9607.601	3249.773	1733.144	96.65601
18	12634.25	9279.318	3111.019	1650.071	88.66107
19	12206.74	8956.557	2974.265	1565.664	
20	11790.44	8646.413		1480.002	
21	11392.88	8352.709			
22	11017.02	8075.361			
23	10661.27	7811.256			
24	10320.92	7555.811			
25	9990.057	7304.423			

TABLE F1: Available energy from each submarine battery at several transit speeds, 80% depth of discharge. (Page two of two).



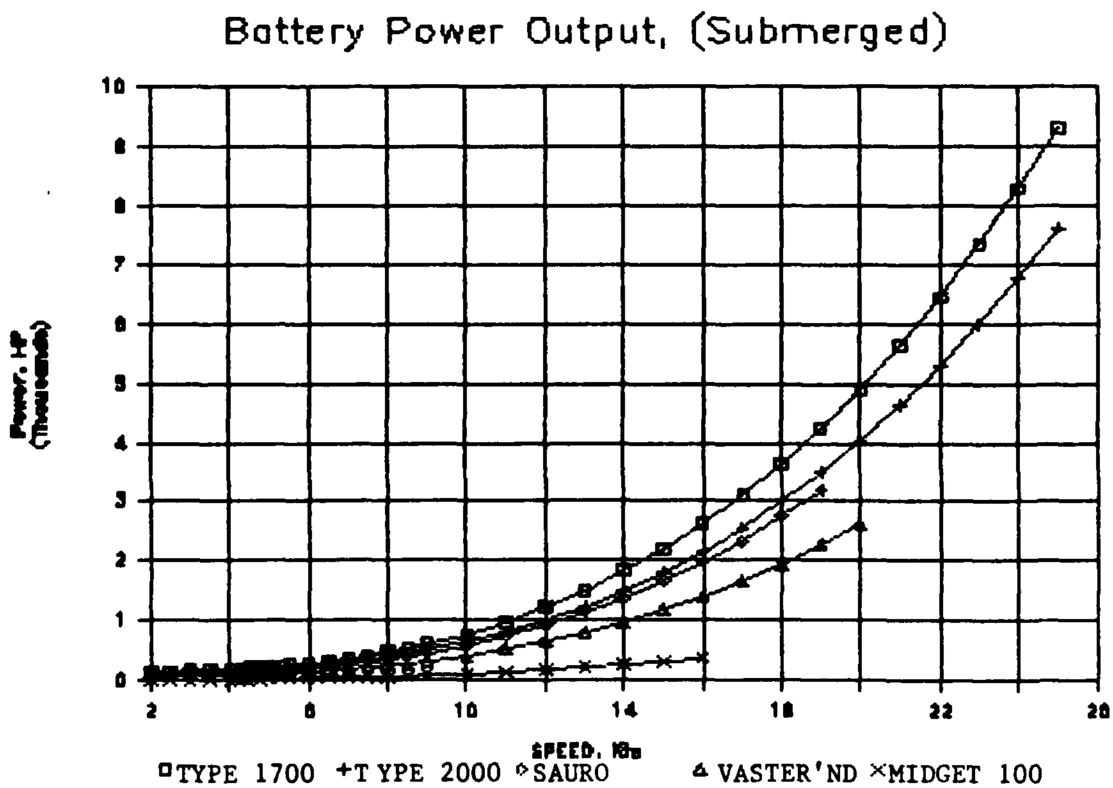
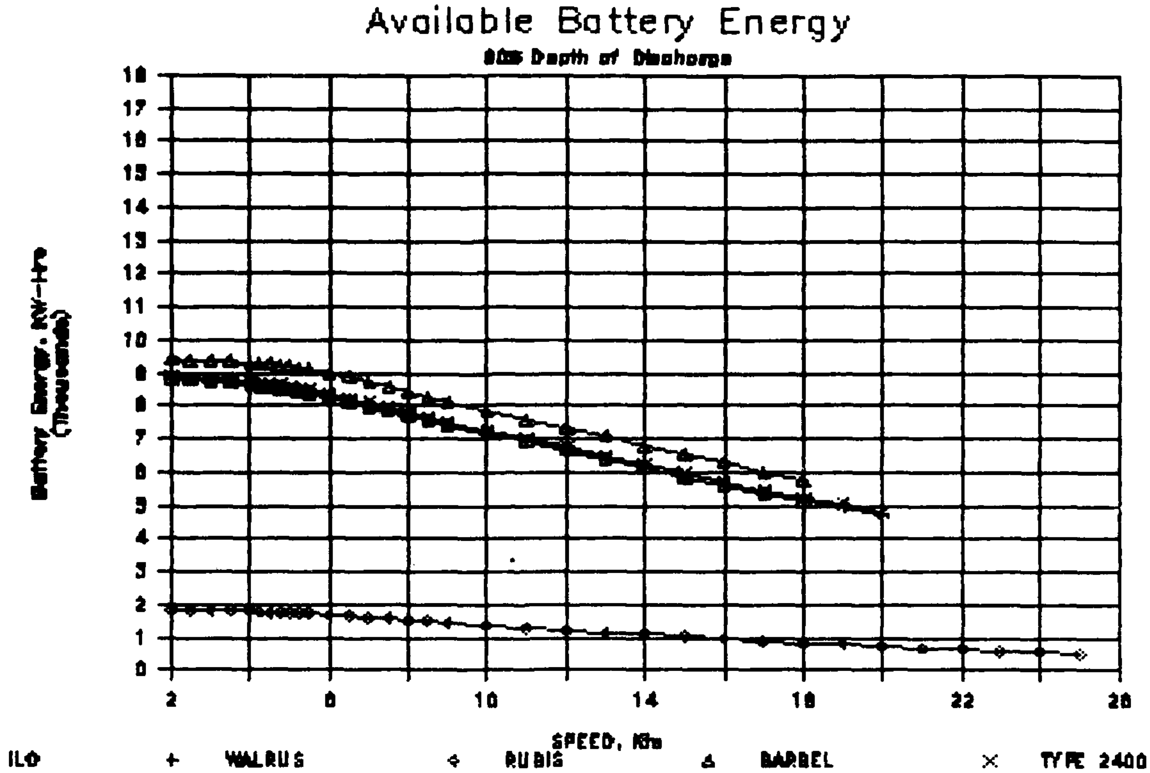


Figure F-1: Total battery power output at various speeds, 80% DoD.



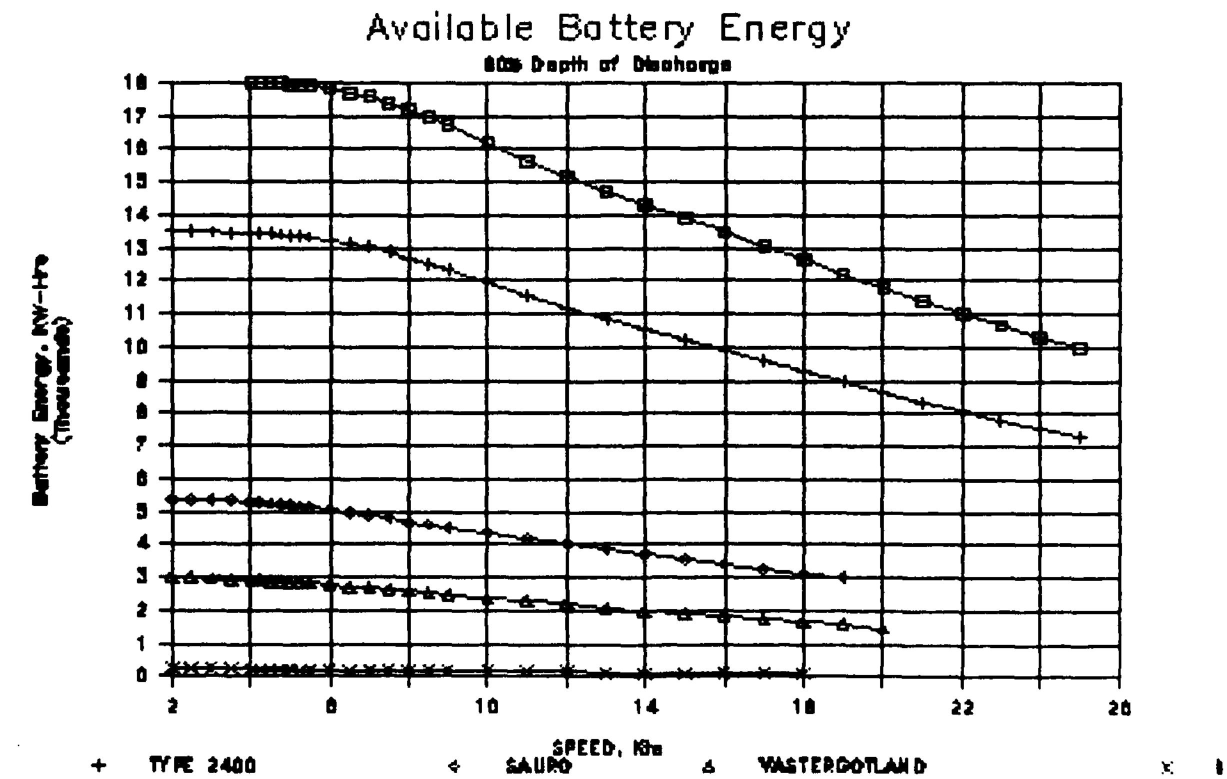


Figure F -2 : Available battery energy at various speeds, 80% DoD.

APPENDIX G: CALCULATION OF BATTERY ENDURANCE RANGE

Once the battery power and energy capacities are determined, the submerged endurance as a function of speed may be calculated. The battery range falls off with increasing speed even more quickly than the fuel endurance range, because the submarine is fighting the non-linear dissipative effects of battery internal resistance as well as the non-linear external resistance of the sea.

The maximum range which a diesel-electric submarine may achieve depends upon elements (1) through (8) detailed in Appendix E, and also upon factors which relate to the submarine's battery capacity. The following relations, adapted from References (3) and (20), may be used to calculate battery endurance range:

$$Mb = (V)(Td) \qquad \text{EQN G-1}$$

$$Td = (DoD)(Eb)/[(SHP/1.34)+Lh] \qquad \text{EQN G-2}$$

$$Eb = Eb(Td) \quad \text{(Given by EQN F-1)} \qquad \text{EQN G-3}$$

where:

- Mb = Endurance range on batteries, Nm.
- Td = Service life, Hrs. The time required to discharge the battery to a given end-voltage at a given discharge rate.
- V = Speed (submerged), Kts.
- DoD = Depth of discharge, Non-Dimensional;

  DoD is taken to be 0.80, (80% discharged).

- Eb = Battery energy at the specific discharge rate, (A function of Td), KW-Hrs.
- SHP = Shaft Horsepower at the speed, HP.
- Lh = Hotel electric load, KW. See Appendix M.
- 1.34 = Conversion factor, HP/KW.

Note that because Eb, Td, and Mb are interdependent, Equations G-1 through G-3 must be solved iteratively. The results of the iterative calculations are listed in Table G-1.

The procedure is to iterate beween Equations G-2 and F-1 to solve for Td, then evaluate G-1 to find the range.

Table G1 lists the numerical values resulting from this procedure, for the appropriate speed ranges for each submarine.

SUBMARINE NAME					
ENDURANCE RANGE (BATTERY)	KILO	WALRUS	RUBIS	BARBEL	TYPE 2400
SPEED, Kts					
2	129.1569	136.2082	27.54910	191.1196	147.1608
2.5	155.9630	164.3386	33.25911	230.0709	177.5176
3	178.2041	187.5513	37.99322	261.8180	202.5429
3.5	194.9291	204.8429	41.55321	285.0229	221.1603
4	205.6549	215.7262	43.84194	299.1382	232.8539
4.25	208.7679	218.7763	44.51084	302.8524	236.1200
4.5	210.4480	220.3103	44.87703	304.4705	237.7510
4.75	210.7816	220.4248	44.95829	304.1409	237.8517
5	209.8777	219.2402	44.77664	302.0408	236.5517
5.25	207.8625	216.8942	44.35718	298.3668	233.9991
5.5	204.8727	213.5348	43.72687	293.3259	230.3527
6	196.5362	204.3850	41.94480	279.9795	220.4325
6.5	185.9728	192.9699	39.64785	263.6053	208.0579
7	174.1616	180.3253	37.03366	245.6049	194.3453
7.5	161.8850	167.2717	34.26950	227.1004	180.1849
8	149.7087	154.3967	31.48807	208.9150	166.2204
8.5	137.9987	142.0751	28.78729	191.5936	152.8671
9	126.9597	130.5109	26.23251	175.4477	140.3544
10	107.1760	109.9059	21.68530	147.0886	118.1357
11	90.37202	92.51592	17.90602	123.6912	99.47748
12	76.20073	77.91603	14.79010	104.4173	83.86639
13	64.31188	65.70095	12.21102	88.43434	70.81297
14	54.41372	55.54604	10.07317	75.11599	59.93909
15	46.24085	47.16821	8.310787	64.01748	50.93844
16	39.52370	40.28832	6.872713	54.79870	43.52693
17	33.98994	34.62708	5.711075	47.16347	37.42380
18	29.38857	29.92661	4.777000	40.83357	32.36378
19		25.97257	4.022209		28.11881
20		22.60194	3.403562		24.50983
21			2.886774		
22			2.447233		
23			2.068519		
24			1.740117		
25			1.455271		

TABLE G1: Calculated values of each submarine's endurance range on batteries alone, 80% depth of discharge. (Sheet one of two).

ENDURANCE RANGE (BATTERY)	SUBMARINE NAME				
	TYPE 1700	TYPE 2000	SAURO	VASTER-GOTL'D	MIDGET 100
SPEED, Kts					
2	302.4685	241.5707	118.0259	90.32605	29.88167
2.5	366.1343	293.3861	142.5852	109.0456	35.83750
3	419.8546	337.9660	163.0220	124.5662	40.58154
3.5	461.5464	373.6454	178.4682	136.2320	43.91500
4	490.1134	399.3912	188.4733	143.7189	45.78124
4.25	499.4450	408.4302	191.4304	145.9008	46.18636
4.5	505.5959	414.9551	193.0821	147.0919	46.26667
4.75	508.7283	419.0537	193.5052	147.3553	46.04954
5	509.0492	420.8519	192.7975	146.7695	45.56589
5.25	506.7977	420.5063	191.0723	145.4244	44.84859
5.5	502.2342	418.1963	188.4533	143.4166	43.93107
6	487.2548	408.4709	181.0471	137.8071	41.62561
6.5	466.2484	393.2991	171.5806	130.6975	38.89275
7	441.1810	374.2651	160.9425	122.7391	35.93971
7.5	413.7410	352.7973	149.8417	114.4356	32.93212
8	385.3042	330.1046	138.7904	106.1409	29.99403
8.5	356.9394	307.1529	128.1200	98.08144	27.21029
9	329.4335	284.6683	118.0180	90.38883	24.63053
10	278.9504	242.9399	99.79719	76.34026	20.14281
11	235.9184	206.9302	84.20427	64.17872	16.48305
12	200.3205	176.7700	70.99404	53.86472	13.49009
13	171.1339	151.7062	59.89765	45.27508	11.02197
14	147.0841	130.7787	50.67037	38.22104	8.987401
15	127.0458	113.1491	43.06617	32.45918	7.330169
16	110.1652	98.18608	36.82178	27.72909	6.003528
17	95.83653	85.43737	31.67161	23.79750	4.953114
18	83.63180	74.57120	27.37721	20.48239	4.116832
19	73.23236	65.32347	23.74723	17.65435	
20	64.37877	57.46281		15.22636	
21	56.84130	50.77458			
22	50.40887	45.06009			
23	44.89010	40.14273			
24	40.11850	35.87361			
25	35.95604	32.13314			

TABLE G1: Calculated values of each submarine's endurance range on batteries alone, 80% depth of discharge. (Sheet two of two).

APPENDIX H: CALCULATION OF INDISCRETION RATE AND INDISCRETION INTERVAL

The necessity to charge the storage batteries requires the diesel-electric submarine to operate, for some portion of time, either on the surface or snorting near the surface. The ratio of the time spent on or near the surface to the total time spent in transit is called the indiscretion rate, and it is desirable to keep it as low as possible.

---

(1) Electric generator/alternator power capacity.
(2) Number and size of cells in the battery.
(3) Type of battery.
(4) Ability to control the charging parameters for optimal charging profile, (closed-loop control).
(5) Vessel transit speed and associated SHP.
(6) Hotel electric load.

Factors affecting indiscretion rate.

Calculation of the indiscretion rate may be performed as follows:

$$IR = Tr/(Tr + Td) \qquad \text{EQN H-1}$$

$$Tr = \frac{(DoD)(Eb)}{(Pdg - (SHP/1.34) - Lh)(Nbc)} \qquad \text{EQN H-2}$$

where:

IR = Indiscretion rate, non-dimensional fraction.
Tr = Time to recharge battery, Hrs.
Td = Battery service life, evaluated at a given speed, Hrs.
DoD = Depth of discharge of the battery.

DoD = 0.8, non-dimensional.

Eb = Battery energy capacity at the rate of discharge, KW-Hrs.
Pdg = Power of the diesel/generators, KW.
SHPw = Shaft horsepower required at the transit speed, operations near the surface, HP.
Lh = Hotel electric load, KW.
Nbc = Average efficiency of electrical-to-chemical energy conversion in the charging of the battery.

Nbc = 0.7 - 0.8, Reference (20), assumed to equal 0.75 for this study.

The calculated values of indiscretion rate are listed in Table H1. Note that the Shaft horsepower used in Equation H-2 is the "near the surface" value, since the submarine is operating near the surface when snorkeling to recharge its batteries. The speed range Listed in Table H1 extends naturally, only to each submarine's max snorkel speed.

The indiscretion interval at a given speed is the duration of time a submarine may transit at the speed, while completely submerged and without snorkeling. It is actually another name for the battery service life at the given speed. Table H2 lists the calculated values of indiscretion interval for each submarine's submerged speed range.

Note that the average electrical-to-chemical energy conversion efficiency is used. It is suitable for comparison purposes, but assumes a constant charging rate. The actual charging rate and charging efficiency is a function of the recharge power, since the same internal resistance factors are at work in the recharging process as in the discharging process. So shorter recharge times are less efficient (and hence longer) than indicated in this first-order calculation.

INDISCRETION RATE	SUBMARINE NAME: KILO	WALRUS	RUBIS	BARBEL	TYPE 2400
SPEED, Kts	INDISCRETION RATE, Fraction				
2	0.040950	0.033859	N/A	0.036584	0.064304
2.5	0.042372	0.035066	N/A	0.037974	0.066589
3	0.044472	0.036852	N/A	0.040022	0.069962
3.5	0.047389	0.039335	N/A	0.042858	0.074644
4	0.051272	0.042643	N/A	0.046622	0.080866
4.25	0.053623	0.044648	N/A	0.048898	0.084630
4.5	0.056276	0.046911	N/A	0.051463	0.088871
4.75	0.059251	0.049452	N/A	0.054338	0.093623
5	0.062571	0.052289	N/A	0.057547	0.098921
5.25	0.066256	0.055440	N/A	0.061109	0.104794
5.5	0.070329	0.058926	N/A	0.065049	0.111275
6	0.079723	0.066978	N/A	0.074158	0.126196
6.5	0.090938	0.076608	N/A	0.085084	0.143950
7	0.104135	0.087959	N/A	0.098021	0.164754
7.5	0.119408	0.101130	N/A	0.113094	0.188694
8	0.136911	0.116251	N/A	0.130488	0.215931
8.5	0.156766	0.133431	N/A	0.150339	0.246549
9	0.179105	0.152784	N/A	0.172774	0.280608
10	0.232437	0.198917	N/A	0.226609	0.360257
11		0.254948	N/A		
12		0.322926	N/A		
13			N/A		
14			N/A		
15			N/A		
16			N/A		
17			N/A		
18			N/A		
19			N/A		
20			N/A		
21			N/A		
22			N/A		
23			N/A		
24			N/A		
25			N/A		

TABLE H1: Calculated values of indiscretion rate at various speeds. Note that only speeds up to the maximum snorkel speed are listed, since the batteries may be charged only while surfaced or snorkeling. (Sheet one of two).

SUBMARINE NAME					
INDISCRETION RATE	TYPE 1700	TYPE 2000	SAURO	VASTER-GOTL'D	MIDGET 100
SPEED, Kts	INDISCRETION RATE, Fraction				
2	0.035838	0.041076	0.057321	0.057359	N/A
2.5	0.036997	0.042264	0.059275	0.059352	N/A
3	0.038700	0.044008	0.062158	0.062287	N/A
3.5	0.041048	0.046411	0.066158	0.066354	N/A
4	0.044144	0.049582	0.071474	0.071748	N/A
4.25	0.046005	0.051490	0.074690	0.075005	N/A
4.5	0.048094	0.053632	0.078312	0.078669	N/A
4.75	0.050425	0.056025	0.082369	0.082768	N/A
5	0.053013	0.058683	0.086889	0.087330	N/A
5.25	0.055872	0.061623	0.091897	0.092375	N/A
5.5	0.059020	0.064862	0.097419	0.097927	N/A
6	0.066249	0.072309	0.110113	0.110658	N/A
6.5	0.074855	0.081190	0.125183	0.125741	N/A
7	0.085001	0.091669	0.142806	0.143362	N/A
7.5	0.096830	0.103880	0.163065	0.163592	N/A
8	0.110527	0.118008	0.186119	0.186672	N/A
8.5	0.126257	0.134213	0.212083	0.212809	N/A
9	0.144175	0.152640	0.241072	0.242234	N/A
10	0.187408	0.197101	0.309386	0.313289	N/A
11	0.240259	0.251248	0.390218		N/A
12	0.303947	0.316820			N/A
13	0.378685	0.394424			N/A
14	0.461881	0.480992			N/A
15	0.549989	0.572121			N/A
16					
17					
18					
19					
20					
21					
22					
23					
24					
25					

TABLE H1: Calculated values of indiscretion rate at various speeds. Note that only speeds up to the maximum snorkel speed are listed, since the batteries may be charged only while surfaced or snorkeling. (Sheet two of two).

SUBMARINE NAME					
INDISCRETION INTERVAL	KILO	WALRUS	RUBIS	BARBEL	TYPE 2400
SPEED, Kts	INDISCRETION INTERVAL, HOURS, (80% DISCHARGE)				
2	64.57398	68.10035	N/A	95.55879	73.57759
2.5	62.38017	65.73116	N/A	92.02707	71.00375
3	59.39552	62.51198	N/A	87.27090	67.51031
3.5	55.68707	58.52031	N/A	81.43254	63.18358
4	51.40541	53.92389	N/A	74.78071	58.20699
4.25	49.11280	51.46832	N/A	71.25471	55.55033
4.5	46.75641	48.94855	N/A	67.65441	52.82534
4.75	44.36453	46.39511	N/A	64.02281	50.06490
5	41.96436	43.83718	N/A	60.40002	47.30030
5.25	39.58113	41.30165	N/A	56.82224	44.56035
5.5	37.23747	38.81245	N/A	53.32102	41.87067
6	32.74365	34.05160	N/A	46.64965	36.72613
6.5	28.59932	29.67545	N/A	40.53916	31.99617
7	24.86948	25.74957	N/A	35.07023	27.75161
7.5	21.57538	22.29317	N/A	30.26445	24.01399
8	18.70578	19.29140	N/A	26.10030	20.76847
8.5	16.22859	16.70787	N/A	22.52835	17.97679
9	14.10102	14.49539	N/A	19.48413	15.58857
10	10.71286	10.98578	N/A	14.70179	11.80856
11	8.210790	8.405691	N/A	11.23890	9.038598
12	6.344672	6.487628	N/A	8.695785	6.983612
13	4.941292	5.048126	N/A	6.796511	5.441397
14	3.881065	3.961882	N/A	5.358868	4.275535
15	3.077707	3.139446	N/A	4.261323	3.390530
16	2.465939	2.513653	N/A	3.418984	2.715791
17	1.995651	2.033081	N/A	2.769198	2.197400
18	1.629179	1.659051	N/A	2.264128	1.794366
19	0	1.363428	N/A	0	1.476408
20	0	1.126341	N/A	0	1.221828
21	0	0	N/A	0	0
22	0	0	N/A	0	0
23	0	0	N/A	0	0
24	0	0	N/A	0	0
25	0	0	N/A	0	0

Table H2: Calculated values of indiscretion interval as a function of submerged speed. This is the same as the battery discharge time at a given speed. (Sheet one of two).

INDISCRETION INTERVAL	TYPE 1700	TYPE 2000	SAURO	VASTER-GOTL'D	MIDGET 100
	SUBMARINE NAME				
SPEED, Kts	INDISCRETION INTERVAL, HOURS, (80% DISCHARGE)				
2	151.2342	120.7853	58.98672	45.12221	14.93813
2.5	146.4537	117.3544	57.00584	43.57625	14.33238
3	139.9515	112.6553	54.30961	41.47874	13.52465
3.5	131.8704	106.7558	50.95640	38.87891	12.54469
4	122.5283	99.84776	47.08008	35.88467	11.44289
4.25	117.5164	96.10118	45.00243	34.28466	10.86495
4.5	112.3546	92.21217	42.86554	32.64261	10.27902
4.75	107.1007	88.22173	40.69505	30.97849	9.692122
5	101.8098	84.17023	38.51571	29.31140	9.110573
5.25	96.53293	80.09622	36.35051	27.65890	8.539868
5.5	91.31537	76.03540	34.22010	26.03655	7.984606
6	81.20922	68.07801	30.13209	22.93284	6.934391
6.5	71.73067	60.50679	26.35806	20.07671	5.979915
7	63.02610	53.46536	22.95727	17.50754	5.130351
7.5	55.16582	47.03825	19.94896	15.23460	4.386905
8	48.16351	41.26146	17.32286	13.24622	3.745252
8.5	41.99348	36.13393	15.05003	11.51864	3.197403
9	36.60444	31.62816	13.09216	10.02300	2.733175
10	27.89585	24.29276	9.959791	7.612412	2.011075
11	21.44787	18.81106	7.633588	5.811186	1.495059
12	16.69398	14.73036	5.893194	4.465660	1.120054
13	13.16464	11.66938	4.584501	3.461733	0.842889
14	10.50646	9.341067	3.598088	2.711770	0.636652
15	8.470181	7.543012	2.852361	2.147554	0.483715
16	6.885829	6.136362	2.284675	1.717324	0.370917
17	5.637999	5.025463	1.847315	1.383626	0.287503
18	4.646802	4.142600	1.505118	1.120591	0.224696
19	3.854927	3.437869	1.233151	0.910880	0
20	3.219499	2.872972	0	0.742793	0
21	2.707238	2.417705	0	0	0
22	2.291770	2.048080	0	0	0
23	1.952161	1.745247	0	0	0
24	1.671998	1.494654	0	0	0
25	1.438629	1.285250	0	0	0

Table H2: Calculated values of indiscretion interval as a function of submerged speed. This is the same as the battery discharge time at a given speed. The values given for the MIDGET 100 are termed the battery discharge times only since this sub does not snorkel. (Sheet two of two).

APPENDIX I: ESTIMATION OF WEIGHT GROUPS

The estimation of the weight groups from open literature is difficult. The following empirical relations have been developed to generate weight values for functional groups which were not found in the literature.

Wstr	= (Dsrf)[0.00055*Id + 0.15]	EQN I-1
Wmob	= 0.572(#C) + 2.1(SHPi)^0.64	EQN I-2
Wfb	= 0.05(Dsurf)	EQN I-3
Wwep	= 0.002(VOLw) + 6(#T) + 5	EQN I-4
Wc3i	= 0.00836(VOLc)	EQN I-5
Wfw	= (GPD)(#w)/(300gal/Lton)	EQN I-6
Wss	= 0.04(Dstd) + 0.40(Men)	EQN I-7

where:

#C	= Number of equivalent standard battery cells.
#w	= Number of days subsistence on water tank alone.
#T	= Equivalent number of 21" torpedo tubes.
Dsrf	= Surfaced Displacement, Lton.
Dstd	= Standard Displacement, Lton.
GPD	= Gallons of fresh water consumed per day.
Id	= Immersion depth, meters.
SHPi	= Installed shaft horsepower.
VOLc	= Volume of C3I spaces, cu ft.
VOLw	= Volume of weapons spaces, cu ft.
Wc3i	= Weight of C3I equipment, Lton.
Wfb	= Weight of fixed ballast, Lton.
Wfw	= Weight of fresh water loadout, Lton.
Wmob	= Weight of the mobility machinery, Lton.
Wss	= Weight of ship support functional group, Lton.
Wstr	= Weight of the submarine structure, Lton.
Wwep	= Weight of weapons functional group, Lton.

Equations I-1 and I-2 are adapted from Reference (15). Equations I-3 through I-7 were based loosely on the weight values for the BARBEL, with consideration of the variables which contribute to the weight of a functional group.

After the above equations were evaluated for each submarine, the formula-calculated submerged displacement is compared to the reference submerged displacement, and all of the calculated weights are scaled by a common coefficient in order to bring the calculated displacement equal to the reference displacement.

The computed values for each submarine weight group are shown in Table 8-1.

APPENDIX J: CALCULATION OF ANAEROBIC DIESEL FUEL/OXYGEN LOAD

The anaerobic diesel cycle developed by Sub Sea Oil Services and used in the MIDGET 100 is truly an engineering accomplishment. According to the literature, the submerged endurance range of the MIDGET 100 is unmatched by all vessels within ten times its displacement. The reason for this is the relative energy-to-weight and energy-to-volume densities of fuel oil/oxygen as compared to lead/acid storage batteries.

Since the propulsion plant is "anaerobic" as far as the atmosphere is concerned, the combustion oxygen must be carried along with the submarine.

The following analysis is taken from Reference (3), and shows that the weight of the required oxygen loaded is approximately three-and-a-half times the weight of the fuel oil loaded.

For the combustion of a typical long-chain saturated hydrocarbon, the process balance between reactants and products is:

$$(C_N H_{2N}) + (3N/2)(O_2) = (N)(CO_2) + (N)(H_2O) \qquad \text{EQN J-1}$$

where:

$C_N H_{2N}$ = One mole of long-chain hydrocarbon.

O_2 = One mole of oxygen.

CO_2 = One mole of carbon dioxide.

H_2O = One mole of water.

N = A constant.

Equation J-1 shows that (3N/2) moles of oxygen are needed for the combustion of one mole of fuel oil. Moles may be converted into weights by the following relations:

Element	Molecular Weight
H	2
C	12
O	32

One mole of C_NH_{2N} weighs: $N[(12) + 2*(1)] = 14N$

3N/2 moles of O_2 weigh: $(3N/2)[(2)(16)] = 48N$

48N/14N = 3.428 = Relative weight of required oxygen to fuel.

The minimum weight of the oxygen is 3.428 times that of the fuel oil. Assuming that the amount of oxygen used in combustion is five-percent above the amount needed for stoichiometric balance:

3.428 * 1.05 = 3.600 = Relative weight of loaded oxygen to fuel.

APPENDIX K: FACTORS AFFECTING CREW ENDURANCE

Some of the most important factors which affect crew endurance are listed below. the factors can be grouped into two categories: Vessel-related, and Personnel related.

1. Number of crewmembers, (complement).
2. Quantity of provisions loaded.
3. Fresh water tank capacity.
4. Existence of fresh water distillers.
5. Air purification capability and effectiveness.
6. Space and volume per crewmember.

7. Quality of provisions loaded.
8. Crew discipline and morale.
9. Crew training state as individuals and as a team.
10. Crewmember's ages.
11. Crewmember's previous experience with similar situations.
12. Crewmember's psychological profiles and temperament.

The focus of this study is necessarily directed to items (1) through (6). Hard data for the above factors is only available with consistency for item (1) in the literature, and even then, the sources often disagree. As such, much of the other data is gleaned from drawings that may be provided in the literature, with the author's best estimate of the unprovided data items.

APPENDIX L: VULNERABILITY AND SURVIVABILITY FACTORS

Submarine vulnerability is directly proportional to its detectability of the submarine to acoustic, magnetic, thermal, and visual sensors. The stealth capability of the submarine is its greatest asset as a military device, although it would be pointless militarily to build a submarine which was merely stealthy, without enough endurance to transit to where needed, enough sensor capability to be effective, and enough speed and weaponry to accomplish its mission.

So, the idea, it would seem, is to build a submarine as invulnerable as possible, which means primarily as quiet as possible but also encompasses the ability to defend itself or to escape in the eventuality that it is detected.

Not all submarines have been designed to this philosophy. Some submarines seem to have been designed to withstand the damage from an attack, and continue. This is the concept of survivability. The U.S.S.R. in particular seems to have taken this approach, with and perhaps not only for the purpose of surviving wartime attack, given the poor peacetime safety record of Soviet submarines, Reference (27).

Survivability may be improved by keeping these concepts in mind during the design of the submarine.

---

1. Redundant and separated vital systems and components:
    - (a). MBT blow valves.
    - (b). Propulsion motors.
    - (c). Electric power cables.
    - (d). Diesel generator sets.
    - (e). Battery banks.
2. Strength and toughness of hull material.
3. Using double-hull design.
4. Dividing the pressure hull into watertight compartments.
5. Using fire-resistant materials within the submarine.
6. Adequate and appropriate fire-extinguishing gear.
7. High state of crew training.
8. High state of equipment readiness.
9. Emergency air-breathing apparatus.

Finally, there is the issue of crew survivability and escape in the event that the submarine is sunk. In several instances, the crew would be unable to survive attacks severe enough to sink their submarine. The humane approach is certainly to provide the crew with an escape pod, in the event its use becomes neccessary. Still, some countries prefer not to have an escape pod mounted, due to thier philosophy that the crew will perform more vigorously if the submarine itself is the only ticket home, Reference (15).

APPENDIX M: ESTIMATION OF HOTEL ELECTRIC LOAD

The open literature gives no empirical formulas for hotel electric load. The following relation is the author's best attempt to parameterize this item which is an important factor in the endurance calculations, primarily so that the hotel load of each submarine is calculated by the same formula, rather than some equally arbitrary but non-uniform basis.

$$Lh = 1.5(Vmob) + 4(Vc3i) + 1.5(Vss) + 1(Vwep) \qquad \text{EQN M-1}$$

where:

- Lh = Hotel electric load, KW.
- Vmob = Volume of the mobility machinery, cu ft.
- Vc3i = Volume of C3I equipment spaces, cu ft.
- Vss = Volume of ship support spaces, cu ft.
- Vwep = Volume of weapons spaces, cu ft.

APPENDIX N: DIESEL ENGINE DATA

The power output of each submarine's prime mover (diesel engine/alternator set, except for RUBIS) is of great importance in the calculation of sustained maximum speed while surfaced or snorkeling, and in the calculation of the indiscretion rate. The power output of the main propulsion electric motor used in each submarine is important in the calculation of maximum submerged speed.

The open-literature data on the diesel engines and main-propulsion motors is listed in Table N1.

	SUBMARINE NAME				
PRIME MOVER DATA	KILO	WALRUS	RUBIS	BARBEL	TYPE 2400
MANUFACTURER	MINISTRY OF SHIPBUILDNG	SEMT-PIELSTICK	COMMISSARIAT a L'ENERGIE ATOMIQUE	FAIRBANKS-MORSE	PAXMAN-VALENTA
MODEL	M50?	PA4-V200-VG		38D8	RPA 200SZ
BHP, (EACH)	3000?	2310	~64,000 MAX	1600	1800
CYCLE	4	4	N/A	2	4
CYLYNDERS	12V	12V	(NUCLEAR	8 INLINE	16
SPEED, rpm	1700	1500	REACTOR)	900?	
SUPERCHRGING	?	COMBINED	N/A	MECHANICAL?	MECHANICAL
NUMBER ABOARD	2	3	1	3	2
MOTOR MFGR:	(U.S.S.R.)	HOLEC	JEU-SCHNDR	GE	GEC
MOTOR KW	~3000	4050	7500	2350	4100
REFERENCE	(11,17)	(5,6,16,21)	(9,10,21)	(11,17)	(5,6,10)

	SUBMARINE NAME				
PRIME MOVER DATA	TYPE 1700	TYPE 2000	SAURO	VASTER-GOTLAND	MIDGET 1)0
MANUFACTURER	MTU	MTU	GMT	HEDEMORA VERKSTADER	SSOS
MODEL	16V-652-MB8	?	A210 16M	VRA/1546	?
BHP, (EACH)	1475	1200	965	?	420
CYCLE	4	4?	4?	?	?
CYLYNDERS	16	16?	16	?	?
SPEED, rpm	?	?	?	?	?
SUPERCHRGING	TURBO?	TURBO?	TURBO	TURBO	?
NUMBER ABOARD	4	4	3	2	1
MOTOR MFGR:	SIEMENS	SIEMENS	MCPN	JEU-SCHNDR	(DIESEL IS
MOTOR KW	6600	5500	3200		ANAEROBIC)
REFERENCE	(5,6,15,21)	(5,21)	(5,6)	(6,15,36)	(6,29)

TABLE N1: Diesel engine and electric propulsion motor data.

Abbreviations:

GE - General Electric.
GMT - Grandi Motori Trieste.
JEU-SCHNDR - Jeumont-Schneider.
MTU - Motoren-und Turbinen-Union Friedrichshafen G.m.b.H.
SSOS - Sub Sea Oil Services of Micoperi S.p.A.

APPENDIX O: DATA ON OTHER MODERN SUBMARINES

The literature contained information on several other submarines which were not included in the detailed study. The information shown in Table O1 is taken primarily from References (5), (6), (7), and (17). The individual data entries are not attributed to the specific reference since most entries could be susbstantiated by multiple references.

SUBMARINE NAME	STAND (Lton)	SURFACE (Lton)	SUBSURF (Lton)	DRAFT (ft)	DIAM (ft)	LOA (ft)
	DISPLACEMENTS			DIMENSIONS		
Federal Republic of Germany						
TYPE 205	?	419	450	14.1	15.1	144
MSV 130	130	?	?	8.856	9.84	85.608
TR 1000	1000	?	?	16.4	17.384	196.8
TYPE 206	?	450	498	14.8	15.1	159.4
TR 1700	1760	2140	2350	21.32	24.6	216.5
France						
RUBIS	2250	2385	2670	21	24.9	236.5
AGOSTA	1250	1510	1760	17.7	22.3	221.7
DAPHNE	?	860	1038	15.1	22.3	189.6
NARVAL	?	1635	1910	18	23.6	255.8
Italy						
MIDGET 100	100	?	136	8.5	10	89
SAURO	1280	1480	1660	21	28.9	211.2
The Netherlands						
WALRUS	1900	2450	2800	21.6	27.6	223.1
MORAY 1400	1150	1310	1450	?	21	177.1
Sweden						
VASTERGOTLAND	990	1070	1140	20	20	159.1
NACKEN, (A14)	?	1030	1125	18.4	18.4	162.4
SJOORMEN	?	1075	1400	19	20	167.3
Union of Soviet Socialist Republics						
FOXTROT	1500	1950	2500	20	26.2	300.1
ZULU IV	1550	1950	2300	20	24.3	295.2
ROMEO	1200	1400	1800	18	23.9	251.9
WHISKEY	800	1080	1350	16.1	21.3	249.3
KILO	1900	2500	3200	23	29.5	229.6
United Kingdom						
TRAFALGAR	?	4000	5208	26.9	32.1	280.1
SWIFTSURE	?	4000	4500	27	32.3	272
OBERON	2030	2230	2455	18	26.5	295.2
TYPE 2400	1850	2160	2400	17.7	25	230.6
United States of America						
DARTER	?	1720	2388	19	27.2	284.5
DOLPHIN	?	800	930	18	19.3	152
BARBEL	2146	2315	2639	28	29	219.1

Table 01: Data on several other modern submarines, from the literature. (Sheet one of five).

SUBMARINE NAME	SPEED: SUBSURF (Kts)	SPEED: SURFACE (Kts)	SPEED: SNORKEL (Kts)	PROPULSION PLANT: PRPULSION PLANT TYPE	PROPULSION PLANT: NUMBER OF SHAFTS	PROPULSION PLANT: PROPELLER BLADES
Federal Republic of Germany						
TYPE 205	17	10	?	D/E	1	?
MSV 130	11	8	?	D/E	1	?
TR 1000	20	11	10	D/E	1	?
TYPE 206	17	10	?	D/E	1	?
TR 1700	25	13	15	D/E	1	7?
France						
RUBIS	25	20	N/A	NUC/LQMTL	1	7
AGOSTA	20	11	10	D/E	1	5
DAPHNE	16	13.5	?	D/E	2	?
NARVAL	18	15	?	D/E	2	?
Italy						
MIDGET 100	16	8	N/A	D/E	1	7
SAURO	19.3	11	11	D/E	1	7
The Netherlands						
WALRUS	20	12	12	D/E	1	5
MORAY 1400	20	12	12	D/E	1	5
Sweden						
VASTERGOTLAND	20	11	10	D/E	1	5
NACKEN	20	20	?	D/E	1	5
SJOORMEN	20	15	?	D/E	1	5?
Union of Soviet Socialist Republics						
FOXTROT	16	18	?	D/E	3	?
ZULU IV	16	18	?	D/E	3	?
ROMEO	14	17	?	D/E	2	?
WHISKEY	14	18	?	D/E	2	?
KILO	16	12	10	D/E	1	6
United Kingdom						
TRAFALGAR	32	0		NUC/PWTR	1	?
SWIFTSURE	30	0		NUC/PWTR	1	?
OBERON	17	12	?	D/E	2	?
TYPE 2400	20	12		D/E	1	7
United States of America						
DARTER	19.5	14	?	D/E	2	?
DOLPHIN	0	15	?	D/E	1	?
BARBEL	21	15	10	D/E	1	?

Table 01: Data on several other modern submarines, from the literature. (Sheet two of five).

PROPULSION PLANT CAPACITIES

SUBMARINE NAME	PRPULSION MOTOR (HP)	DIESEL POWER (HP)	ALTER-NATOR (KW)	EMERG MOTOR (HP)	BATTERY WEIGHT (Lton)	NUMBER BATTERY CELLS
Federal Republic of Germany						
TYPE 205	500	1200	900	?	?	?
MSV 130	?	?	?	?	?	18
TR 1000	?	?	?	?	?	?
TYPE 206	800	1500	1150	?	?	?
TR 1700	8844	6000	4400	N/A	518	980
France						
RUBIS	10000	N/A	10500	YES	N/A	N/A
AGOSTA	4500	3600	2700	?	185	320
DAPHNE	2600	1224	900	?	?	?
NARVAL	4800	?	?	?	?	?
Italy						
MIDGET 100	420	120	90	48	5.5	15?
SAURO	3216	2894	2160	N/A	?	296
The Netherlands						
WALRUS	5360	6930	5170	N/A	275	480
MORAY 1400	Various	Various	Various	?	?	?
Sweden						
VASTERGOTLAND	2926	2680	2000	N/A	170	168
NACKEN	?	?	?	?	?	?
SJOORMEN	?	2200	1640	?	?	?
Union of Soviet Socialist Republics						
FOXTROT	5500	6000	4500	?	?	?
ZULU IV	5500	6000	4500	?	?	?
ROMEO	4000	4000	3000	?	?	?
WHISKEY	2700	4000	3000	?	?	?
KILO	4000	6000	4500	?	275?	480?
United Kingdom						
TRAFALGAR	15000	4000	3000	?	?	?
SWIFTSURE	15000	4000	3000	?	?	?
OBERON	6000	3680	2740	?	275	480
TYPE 2400	5400	3618	2500	N/A	275	480
United States of America						
DARTER	5500	4500	3375	?	?	?
DOLPHIN	650	1650	1200	?	?	?
BARBEL	3150	4800	3580	N/A	290	504

Table 01: Data on several other modern submarines, from the literature. (Sheet three of five).

SUBMARINE NAME	RANGE AND DEPTH CAPABILITIES: ENDURANCE RANGE (Nm)	BATTERY RANGE (Nm)	PROVISION ENDURANCE (Days)	DIVE DEPTH (m)	MANNING: COMPLMNT OFFICER	COMPLMNT ENLISTED
Federal Republic of Germany						
TYPE 205	?	?	?	?	4	18
MSV 130	?	?	14	130	5, (+8)	0
TR 1000	?	?	40	?	21 TOTAL	-
TYPE 206	?	?	?	150	4	18
TR 1700	12000+	~450	70	300	8	22
France						
RUBIS	?	?	60	300	9	57
AGOSTA	10500	350	65	250	4	45
DAPHNE	?	?	?	?	6	39
NARVAL	?	?	?	?	56	7
Italy						
MIDGET 100	1600	~15	14	200	4	8
SAURO	12500	?	45	300	7?	38?
The Netherlands						
WALRUS	10000	200 @ 2 K	60-80	300	7	43
MORAY 1400	9500	?	50	300	7	29
Sweden						
VASTERGOTLAND	?	?	30	300	7	13
NACKEN	?	?	?	?	21 TOTAL	-
SJOORMEN	?	?	?	?	23 TOTAL	-
Union of Soviet Socialist Republics						
FOXTROT	?	?	?	?	75 TOTAL	-
ZULU IV	?	?	?	?	75 TOTAL	-
ROMEO	?	?	?	?	55 TOTAL	-
WHISKEY	?	?	?	?	55 TOTAL	-
KILO	8000?	?	45	300?	55 TOTAL	-
United Kingdom						
TRAFALGAR	?	?	?	?	12	85
SWIFTSURE	?	?	?	?	12	85
OBERON	12000	?	56	300	7	61
TYPE 2400	7000+	?	49	200	7	37
United States of America						
DARTER	?	?	?	?	8	75
DOLPHIN	?	?	?	?	7	15
BARBEL	?	?	60	120?	8	69

Table 01: Data on several other modern submarines, from the literature. (Sheet four of five).

WEAPONS SYSTEMS

SUBMARINE NAME	BOW TUBES	DIAM (in)	OTHER TUBES	RELOADS CARRIED	CRUISE MISSILE?	MINE LAYING?
Federal Republic of Germany						
TYPE 205	8	?	0	8	?	?
MSV 130	0	?	4,EXT	4	?	?
TR 1000	6	21?	0	6	NO?	YES?
TYPE 206	8	?	0	8	?	?
TR 1700	6	21	0	22	NO	YES?
France						
RUBIS	4	21	0	10	YES	YES
AGOSTA	4	21	0	16	YES	YES
DAPHNE	8	?	4,S	12	?	?
NARVAL	6	?	0	20	?	?
Italy						
MIDGET 100	4	15+	0	4	NO	YES
SAURO	6	21+	0	6	NO	YES?
The Netherlands						
WALRUS	4	21	0	20	YES	YES
MORAY 1400	6	21?	0	12	?	YES?
Sweden						
VASTERGOTLAND	4	21+	3,15-in	6	NO	YES
NACKEN	6	21	2,15-in	8	NO	YES
SJOORMEN	4	?	2,S	6	?	?
Union of Soviet Socialist Republics						
FOXTROT	6	?	4,S	22	YES?	YES
ZULU IV	6	?	4,S	22	YES?	YES
ROMEO	6	?	2,S	14	YES?	YES
WHISKEY	4	?	2,S	12	YES?	YES
KILO	8	?	0	10	YES?	YES
United Kingdom						
TRAFALGAR	5	21	0	25	?	?
SWIFTSURE	5	21	0	25	?	?
OBERON	6	21	2,S	14	?	YES
TYPE 2400	6	21	0	18	YES	YES
United States of America						
DARTER	6	21	2,S	8	YES?	YES?
DOLPHIN	0	21	0	0	YES?	YES?
BARBEL	6	21	0	6	YES?	YES?

Table 01: Data on several other modern submarines, from the literature. (Sheet five of five).

APPENDIX P: DIESEL ENGINE SPECIFIC FUEL CONSUMPTION VARIABLES

The specific fuel consumption of modern diesel engines is in the range of approximately 0.30 to 0.35 lbs/HP-Hour, Reference (3). This exceptionally-low SFC is achieved when the engine is run on the test stand, and under the "best" conditions of engine speed and power loading. For other speeds and other power loadings, the SFC is generally greater than this value. The SFC at the actual condition of loading may be approximated graphically by the generic diagram of Figure P-1. Figure P-1 shows that the SFC will increase at power levels other than approximately the 90% power level, and will also increase at engine RPM other than the approximate optimum of 90% of rated maximum RPM.

The specific fuel consumption of the installed diesel engines, while snorkeling, will be greater still than the values predicted by Figure P-1, because of flow resistance in the snorkel intake and uptake.

For the anaerobic diesel engines in the MIDGET 100, the exact SFC under any conditions is not known, since Sub Sea Oil Services has not published the details of their technology. It is reasonable to assume that the SFC of the anaerobic diesel cycle, as a whole, is greater than that of a comparable conventional diesel cycle, since the carbon-dioxide exhaust gas produced, (after any startup transients) must be discharged overboard at ambient pressure.

If the assumption is made that the operators of the diesel engine will operate the engine at the optimum engine speed/power point, then the specific fuel consumption of the installed marine diesel engines, as described by Figure P-1, may be approximated by the following:

$$SFC = 0.40 + 0.30(BHP90\% - BHPop)/(0.65*BHPr) \quad \text{EQN P-1}$$

where:

- SFC = Specific fuel consumption at the actual operating point, lbs/HP-Hr.
- BHP90 = The power output of the engine at its assumed optimum efficiency operating point: 90% of rated power, HP.
- BHPop = The power output of the actual operating point, HP.
- BHPr = The rated power output of the engine, HP.

Assumed values of the SFC for each engine, calculated from Equation P-1, are listed in table P1.

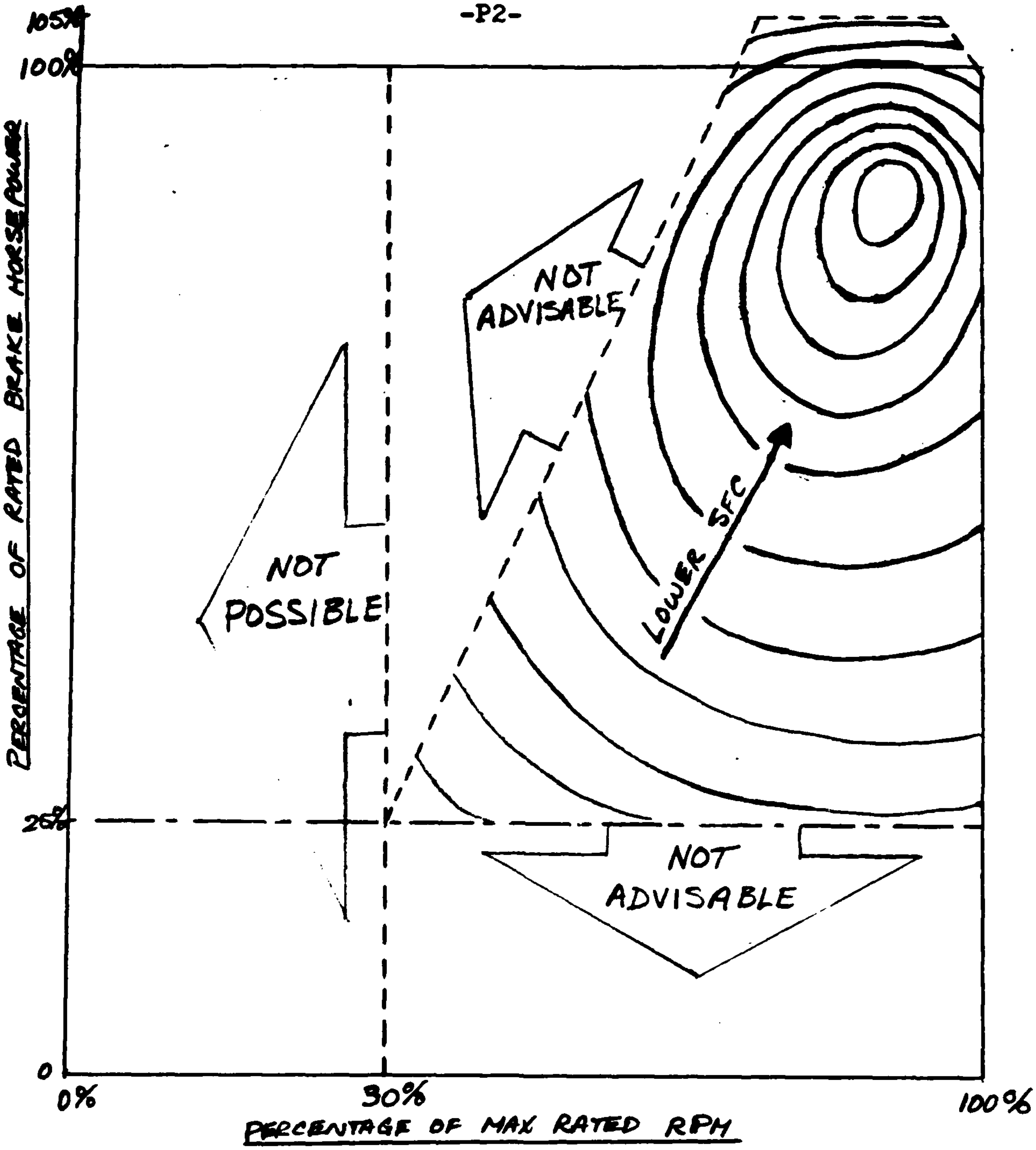


FIGURE P1: DIESEL ENGINE SPECIFIC FUEL CONSUMPTION GENERIC PROFILE. [From Reference (3).]

SUBMARINE NAME					
SFC AT SPEED (ESTIMATED)	KILO	WALRUS	RUBIS	BARBEL	TYPE 2400
NMBR DIESELS	2	3	1	3	2
FOR SINGLE DIESEL					
FULL LOAD BHP	3000	2310	500	1600	1800
90% LOAD BHP	2700	2079	450	1440	1620
SPEED, Kts	SFC = 0.35 + 0.3*@ABS(BHP.90 - BHPop)/(0.65*BHP_FULL)				
2	0.737307	0.730694	0.599248	0.727355	0.724002
2.5	0.736386	0.729522	0.594114	0.725940	0.722584
3	0.735034	0.727799	0.586574	0.723865	0.720500
3.5	0.733172	0.725423	0.576186	0.721008	0.717628
4	0.730721	0.722295	0.562513	0.717250	0.713846
4.25	0.729250	0.720417	0.554308	0.714996	0.711576
4.5	0.727603	0.718314	0.545119	0.712473	0.709034
4.75	0.725769	0.715972	0.534891	0.709665	0.706204
5	0.723740	0.713380	0.523573	0.706559	0.703071
5.25	0.721506	0.710525	0.511109	0.703139	0.699621
5.5	0.719057	0.707395	0.497446	0.699391	0.695839
6	0.713477	0.700262	0.466314	0.690854	0.687220
6.5	0.706924	0.691882	0.429752	0.680832	0.677096
7	0.699322	0.682158	0.387338	0.669211	0.665349
7.5	0.690596	0.670993		0.655876	0.651863
8	0.680672	0.658291		0.640714	0.636522
8.5	0.669475	0.643957		0.623611	0.619210
9	0.656930	0.627893		0.604455	0.599811
10	0.627500	0.590198		0.559534	0.554294
11		0.544445			
12		0.489877			
13					
14					
15					

Table P1: Estimated diesel engine specific fuel consumption, as a function of speed. This calculation assumes the specific fuel consumption dependency with engine loading of Equation P-1, that the battery is not being charged, and that the diesel is supplying power for propulsion and hotel electricity. (Sheet one of two).

SFC AT SPEED (ESTIMATED)	SUBMARINE NAME: TYPE 1700	TYPE 2000	SAURO	VASTER-GOTLAND	MIDGET 100
NMBR DIESELS	4	4	3	2	2
FOR SINGLE DIESEL					
FULL LOAD BHP	1475	1200	965	1340	420
90% LOAD BHP	1327.5	1080	868.5	1206	378
SPEED, Kts					(NOTE 1)
2	0.715395	0.707799	0.706846	0.734831	0.742362
2	0.713772	0.706140	0.704970	0.733858	0.741513
2	0.711391	0.703709	0.702217	0.732434	0.740271
2	0.708112	0.700367	0.698428	0.730475	0.738563
2	0.703796	0.695975	0.693444	0.727903	0.736320
2	0.701206	0.693342	0.690454	0.726361	0.734977
2	0.698307	0.690396	0.687106	0.724635	0.733473
2	0.695080	0.687119	0.683381	0.722716	0.731801
2	0.691509	0.683494	0.679259	0.720594	0.729951
2	0.687577	0.679504	0.674722	0.718258	0.727916
2	0.683267	0.675134	0.669749	0.715699	0.725688
2	0.673449	0.665182	0.658421	0.709874	0.720613
2	0.661919	0.653506	0.645121	0.703041	0.714661
2	0.648546	0.639972	0.629698	0.695121	0.707765
2	0.633197	0.624449	0.612001	0.686039	0.699856
2	0.615742	0.606807	0.591876	0.675718	0.690869
2	0.596049	0.586914	0.569176	0.664081	0.680737
2	0.573987	0.564641	0.543749	0.651053	0.669395
2	0.522239	0.512437	0.484118	0.620522	0.642817
11	0.459461	0.449164	0.411795		0.610612
12	0.384624	0.373798			0.572261
13	0.403297	0.414677			0.527248
14	0.505325	0.517277			0.475059
15	0.622475	0.635009			0.415182

Table P1: Estimated diesel engine specific fuel consumption, as a function of speed. This calculation assumes the specific fuel consumption dependency with engine loading of Equation P-1, that the battery is not being charged, and that the diesel is supplying power for propulsion and hotel electricity. NOTE: For MIDGET 100, the diesel is providing propulsive power only. (Sheet two of two).

APPENDIX Q: CALCULATION OF PROVISIONING ENDURANCE

The provision endurance range is based primarily upon the foodstores loadout for the crew. It is a linear function with speed, being directly proportional to the speed. For this reason, the actual endurance range of a submarine may be far less than had been calculated from the consideration of the bunker fuel loadout alone. At low speeds, the submarine range is limited by the loadout of foodstores, since those are exhausted prior to the exhaustion of bunker fuel.

The provisioning endurance range may be expressed as:

$$Mpr = (\#P)(V)(24) \qquad \text{EQN Q-1}$$

where:

Mpr = Endurance range based on provisions, Nm.
#P = Number of days of provision loadout.
V = Speed of travel, Kts.
24 = Conversion factor, hours/day.

The comparison of fuel endurance range to provision endurance range is shown in Figures in Chapter X.

PROVISIONING ENDURANCE	KILO	WALRUS	RUBIS	BARBEL	TYPE 2400
SPEED, Kts		PROVISIONING ENDURANCE, Nm			
2	2160	3360	2880	2880	2352
2.5	2700	4200	3600	3600	2940
3	3240	5040	4320	4320	3528
3.5	3780	5880	5040	5040	4116
4	4320	6720	5760	5760	4704
4.25	4590	7140	6120	6120	4998
4.5	4860	7560	6480	6480	5292
4.75	5130	7980	6840	6840	5586
5	5400	8400	7200	7200	5880
5.25	5670	8820	7560	7560	6174
5.5	5940	9240	7920	7920	6468
6	6480	10080	8640	8640	7056
6.5	7020	10920	9360	9360	7644
7	7560	11760	10080	10080	8232
7.5	8100	12600	10800	10800	8820
8	8640	13440	11520	11520	9408
8.5	9180	14280	12240	12240	9996
9	9720	15120	12960	12960	10584
10	10800	1680C	14400	14400	11760

PROVISIONING ENDURANCE	TYPE 1700	TYPE 2000	SAURO	VASTER-GOTL'D	MIDGET 100
SPEED, Kts		PROVISIONING ENDURANCE, Nm			
2	3360	4320	2160	1440	672
2.5	4200	5400	2700	1800	840
3	5040	6480	3240	2160	1008
3.5	5880	7560	3780	2520	1176
4	6720	8640	4320	2880	1344
4.25	7140	9180	4590	3060	1428
4.5	7560	9720	4860	3240	1512
4.75	7980	10260	5130	3420	1596
5	8400	10800	5400	3600	1680
5.25	8820	11340	5670	3780	1764
5.5	9240	11880	5940	3960	1848
6	10080	12960	6480	4320	2016
6.5	10920	14040	7020	4680	2184
7	11760	15120	7560	5040	2352
7.5	12600	16200	8100	5400	2520
8	13440	17280	8640	5760	2688
8.5	14280	18360	9180	6120	2856
9	15120	19440	9720	6480	3024
10	16800	21600	10800	7200	3360

Table Q1: Provisioning endurance, in nautical miles, at various speeds.

APPENDIX R: ESTIMATION OF PRISMATIC COEFFICIENT

The prismatic coefficient of each submarine is found by first calculating the envelope volume, which will have tha dispalcement of the submarine while submerged, plus free flood, which may be assumed to be approximately five percent. The volume s of the appendages and sail are then estimated from pictures in the literature, and are subtracted from the envelope volume. The result of this calculation is the bare-hull volume.

The ratio of the volume of the bare hull to the volume described by the product of the maximum section area and the length overall is the prismatic coefficient.

The calculated values for prismatic coefficient are shown in Table R1.

SUBMARINE NAME

PRISMATIC COEFFICIENT, Cp	KILO	REF	WALRUS	REF	RUBIS	REF	BARBEL	REF	TYPE 2400	REF
LENGTH, (ft)	229.6	(17)	223.1	(23)	236.5		219.1	(17)	230.6	(32)
BEAM, (ft)	29.5	(17)	27.6	(23)	24.9		29	(17)	25	(32)
TOTAL ENVLPE VOL	117600		102900		98122		96983		88200	
(MINUS) SAIL VOL	-1500	(e)	-1273		-2037		-1900		-2460	
MINUS APPDGE VOL	-200	(e)	-118		-220		-230		-240	
BAREHULL ENV VOL	115900		101509		95865		94853		85500	
PRISMATIC COEFF.	0.738		0.760		0.832		0.655		0.755	
L/D RATIO:	7.783		8.083		9.497		7.555		9.224	
HULL SURF AREA	18000	(e)	16705		17039		15436		16316	
Cws	0.845		0.863		0.921		0.773		0.900	
REFERENCE DRAWING FOR MEASUREMENTS:	(e)		(18)		(10)		(35)		(13)	

	TYPE 1700	REF	TYPE 2000	REF	SAURO	REF	VASTER-GOTL'D	REF	MIDGET 100	REF
LENGTH, (ft)	216.5	(7)	210.6	(6)	211.2		159.1		88.9	
BEAM, (ft)	23.9	(7)	24.4	(6)	22.3		20.3		10.3	
TOTAL ENVLPE VOL	86362		85628		61005		41895		4998	
(MINUS) SAIL VOL	-2200		-1232		-1450		-960		-160	
MINUS APPDGE VOL	-155		-215		-154		-50		-37	
BAREHULL ENV VOL	84007		84181		59401		40885		4801	
PRISMATIC COEFF.	0.864		0.854		0.720		0.793		0.648	
L/D RATIO:	9.058		8.631		9.386		7.837		8.631	
HULL SURF AREA	15903		14656		12383		9150		2267	
Cws	0.978		0.907		0.829		0.901		0.788	
REFERENCE DRAWING FOR MEASUREMENTS:	(2)		(e)		(12)		(36)		(29)	

Table R-1: Calculation of prismatic coefficient.